The Scientific and Educational Impact of the University-Based Accelerator Laboratories ARUNA

A white paper submitted to NSAC in January 2015

Executive Summary

ARUNA, the Association for Research at University Nuclear Accelerators, consisting of 10 institutions and 176 registered users, is an association of university-based accelerator laboratories and the scientists performing nuclear research at them. This white paper was produced as the outcome of a workshop held June 12 and 13, 2014 on the campus of the University of Notre Dame. The workshop was attended by 59 registered participants from 20 institutions and centered its discussion around 34 plenary presentations. The program is available at `http://aruna.physics.fsu.edu/Workshop.html`. The goal of the meeting was to document the scientific impact of the programs at the university-based accelerator laboratories and formulate a vision of their future role for the scientific community.

The university-based ARUNA laboratories pursue research programs in nuclear astrophysics, low energy nuclear physics, fundamental symmetries, and a rapidly growing number of nuclear physics applications, building bridges to other research communities. Their efforts are advancing the priorities for low-energy nuclear science as expressed in the NSAC long-range plans, and are also pioneering new initiatives, new scientific directions and developments in the field.

The ARUNA laboratories span a range of sizes and comprise a very diverse portfolio of research instruments and programs. All ARUNA facilities benefit from their location on university campuses, where a large fraction of the research is carried out. The faculty and scientists at these facilities represent an important intellectual resource for the national nuclear program. They not only provide new ideas for their local facilities, but represent a large fraction of the user community for the national laboratories. ARUNA facilities are the testing ground for new ideas and new technical developments; the nation's first radioactive beam facilities were developed at ARUNA laboratories, ARUNA facilities provide now the design for critical instrumentation for FRIB as the major new tool for low energy nuclear physics.

Some ARUNA laboratories have developed unique capabilities in mono-energetic neutrons, high intensity mono-energetic γ–photon beams, providing new ideas for large scale international facilities such as ELI in Europe. ARUNA laboratories have also developed techniques for generating and utilizing high-intensity low-energy beams, which will be an important asset towards the development of the next generation of underground accelerator laboratories. Utilization of these probes is essential for addressing many of the scientific goals and challenges in low energy nuclear physics and astrophysics. The facilities are characterized by their flexibility to perform long term experiments or experimental programs that are not possible within the environment of the national user facilities.

ARUNA laboratories provide an important fraction of the nuclear workforce. Through their location on university campuses, they attract undergraduate and graduate students into the field, and they provide a unique training environment for students and postdocs from a very early stage on. A large fraction of today's nuclear physics research community has been trained at university facilities. The ARUNA laboratories play a major role in the workforce rejuvenation of the national nuclear science endeavor and are often the flagship facilities at their host institutions.

To maintain this role for the broader community continuing support for university based laboratories is essential.

Resolution

In order to ensure the long-term health of the field and the education of the next generation of scientists, it is critical to maintain a balance between funding of major facilities and the needs of university-based programs, for their research operations, science and new initiatives.

1 Introduction

ARUNA (Association for Research at University Nuclear Accelerators) is an association of the accelerator laboratories at Florida State University, Hope College, Ohio University, Texas A&M University, TUNL (Duke University, University of North Carolina at Chapel Hill, North Carolina State University), Union College, the University of Kentucky, the University of Massachusetts Lowell, the University of Notre Dame and the University of Washington. It was founded in 2011 to enhance communication and exchange between the partner institutions and to strengthen the research and educational opportunities at these laboratories.

The ARUNA research programs presented in this white paper are characterized as nuclear astrophysics, low-energy nuclear physics, fundamental symmetries and applications. In cases, overlap with research questions and needs of other science communities exists. ARUNA scientists are primarily funded through DOE and NSF for the nuclear physics core program. Most ARUNA groups operate their facilities as a means to achieve the grant-funded scientific goals, with the exceptions of the Texas A&M cyclotron, TUNL and the University of Washington. These three are operated as DOE Centers of Excellence. Currently (FY 2014), the ARUNA groups receive 15.5 million dollars in grant funding, of which between 20 and 30% are used to support the accelerator operations, a total of around 3.7 million dollars. The grant funding to ARUNA laboratories is strongly leveraged by the hosting universities, which, almost everywhere, over-match the operations budgets by providing staff positions, utilities, and other contributions. The universities consider their respective ARUNA laboratories as scientific flagships with a big role in innovative and independent research developments and a unique role in graduate and, even more so, undergraduate student training.

The National Science Foundation has traditionally made education and training a cornerstone of their research support. The topic of workforce development and its impact on the DOE mission has also become a primary focus at the DOE Office of Science and has been addressed in a report to NSAC [2]. Several challenges in fulfilling the workforce needs of fundamental and applied nuclear science were identified. The report concludes that early exposure of undergraduate students to nuclear methods is a big factor in addressing these needs. All ARUNA laboratories support undergraduate research projects, many are hosts to groups from undergraduate colleges and two ARUNA accelerator labs are located at undergraduate institutions. Through these links, ARUNA laboratories are playing an important role in rejuvenating the nuclear workforce.

During the last four years, the Holifield Radioactive Beam Facility (HRIBF) at Oak Ridge National Laboratory and the Wright Nuclear Structure Laboratory at Yale University have ceased operations. These facilities were supporting internal and external user programs with around 7500 hours of experiment time per year. Access to experimental facilities in low-energy nuclear science has reached a critically low level, which, if it continues, will endanger scientific progress, the quality of education and the number of experimental nuclear Ph.D's. ARUNA laboratories are needed to alleviate the impact of the nationwide reduction in experimental facilities for low-energy nuclear science and nuclear astrophysics.

ARUNA scientists provide intellectual and scientific leadership, not only at their own institutions. They also play a leading role for the nation's nuclear physics endeavor, as users and innovators at national research facilities and through developments for these programs. Many of the scientific goals and developments in the low energy nuclear physics and astrophysics community have been spearheaded, tested, and developed at ARUNA institutions.

The intellectual potential at work in ARUNA provides great benefits for the national nuclear physics program. ARUNA laboratories and their broader intellectual and scientific networks provide the link between disciplines that foster new ideas and innovations. Without their continuous and strengthened support, nuclear physics may well disappear as an academic field from many university campuses.

2 The Scientific Impact of ARUNA: Nuclear Astrophysics

2.1 Introduction

Nuclear Astrophysics is a field where ARUNA laboratories have made fundamental contributions over the last two decades. ARUNA facilities presently assume a leading role in the nuclear astrophysics community. They have pioneered the development of radioactive beams, they are leading in the use of high-intensity stable beams and pioneered new indirect techniques and methods complementing the direct study of nuclear reactions at quiescent and explosive burning. They have initiated a worldwide network of experimentalists, theorists and observers to identify the scientific goals and priorities, and to test the results against predictions and observations.

Figure 1 demonstrates the key role that nuclear physics plays in the universe and in the development of the isotopic and elemental abundances from the first minute to the present time. It shows a snapshot of the distribution of γ radiation from the radioisotope ^{26}Al, a fingerprint of the ongoing nucleosynthesis distributed over the galactic plane. ARUNA scientists lead the laboratory effort for explaining various quiescent and violent nucleosynthesis processes. Their work is not limited to their "home" facilities, but they provide essential contributions to the scientific plan and agenda of FRIB as the world's leading radioactive beam facility.

The following sections will specify the contributions of ARUNA based research in investigating the contributions to stellar burning and in exploring the far-off stability reaction sequences that drive stellar explosion. In addition, this section provides on overview of achievements and long-term research plans at ARUNA laboratories that cannot be performed anywhere else in the United States.

Stellar Burning and Stellar Evolution

Stable-beam experiments have been a major contributor to our understanding of nuclear astrophysics since the field began in the 1930s. Photon beams are a relative newcomer but also have significant impact. Here, we focus on quiescent burning in stars and explosive nucleosynthesis, where significant progress using stable and γ-photon beams is anticipated. This is not to say that these approaches are not useful in other scenarios, for example Big-Bang Nucleosynthesis (BBN). In the case BBN, it is already a triumph of stable-beam experiments that the important reactions have been measured in the Gamow window, although some experimental data still requires re-measurement with higher accuracy and precision. Further experimental work in the area of BBN could be motivated by high-precision primordial abundance measurements, e.g., of deuterium.

Planned stable and γ-photon beam experiments directly address two of the key questions for nuclear science identified in the 2007 Long Range Plan:

- **What is the origin of the elements in the cosmos?**
- **What are the nuclear reactions that drive stars and stellar explosions?**

How Do Stars Work?

Almost all questions in astrophysics ultimately require a detailed understanding of stars and stellar properties, thus challenging stellar models to become more sophisticated, quantitative and realistic in their predictive power. Such improvements demand a more detailed understanding of the input physics, such as thermonuclear reaction rates and opacities. Experimental efforts to measure cross sections and related spectroscopic information address the question of reaction rates and will provide significantly more accurate rates in the future. Ultimately, the improvement of our understanding of stars requires systematic studies from many subfields of science, including: observations, theoretical astrophysics, nuclear experiment, and nuclear theory (e.g., to guide extrapolations of cross sections to lower energies). Observations are taken broadly here to include the entire electromagnetic spectrum as well as neutrino and meteoritic abundances measurements, and are essential for validating stellar models. The systematic nature of this work implies

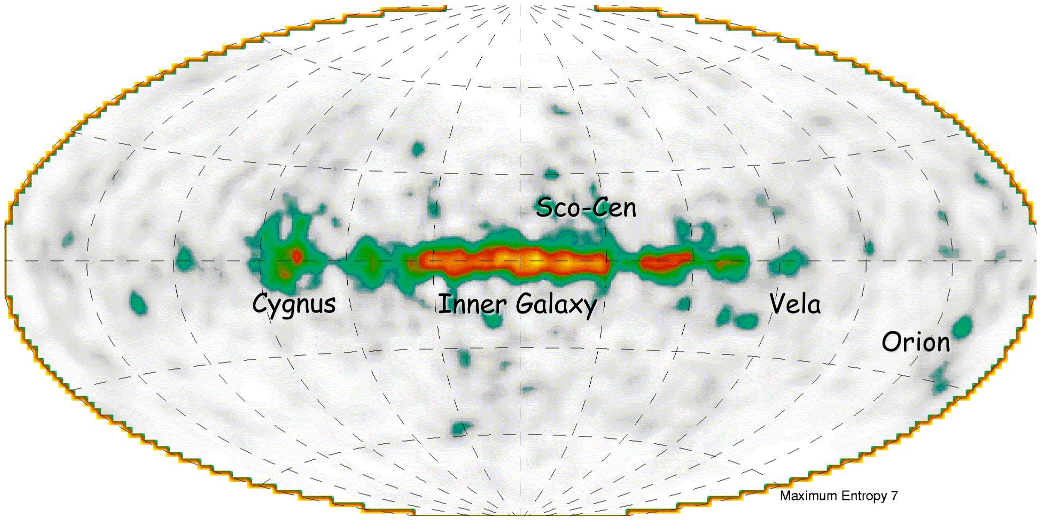


Figure 1: Map of the Galaxy in radioactive ^{26}Al gamma-rays as obtained from the NASA Compton Observatory mission and its COMPTEL telescope (Plueschke et al. 2001).

that a broad range of isotopes is considered and that careful error analysis is undertaken for all ingredients of the models as well as for the observations.

Key areas of interest for stable beams are the *pp* chain and CNO reactions that occur in our sun, due to the continuing interest in the solar neutrinos produced by these processes. The measurements of solar neutrinos (e.g., via the Borexino experiment) have entered a phase of high-precision spectroscopy, making it imperative that the nuclear physics be understood at a comparable level. In general, these reaction rates can be improved via two approaches: (1) improved precision or (2) measurements at lower energies. Measurements at low energies are made difficult by the small cross sections and it should be noted that a lower-energy measurement with poor precision compared with other data is not helpful. What is thus required are dedicated facilities which can supply the beam time and luminosity required to perform the measurements with small statistical and systematic uncertainties. Such facilities are discussed in more detail below. Specific reactions where improvements are desired include ^{3}He$(\alpha,\gamma)^7$Be, ^{12}C$(p,\gamma)^{12}$N, ^{14}N$(p,\gamma)^{15}$O, and ^{17}O$(p,\gamma)^{18}$F.

Hydrogen burning is of fundamental importance in essentially all stars. In addition to the CNO reactions already mentioned, quiescent hydrogen burning can affect abundances all the way up to $A = 40$, and important questions remain to be answered.

After the hydrogen fuel in the core of a star is exhausted, the star enters the helium burning phase. The key reactions here are the triple-alpha process which burns three α particles into ^{12}C and the ^{12}C$(\alpha,\gamma)^{16}$O reaction. In massive stars, which undergo type-II supernova explosions and are largely responsible for enriching the interstellar medium in heavy elements, the rates of these reactions have significant impact on the nucleosynthesis of elements in the $A = 12 - 40$ range and also have important consequences for understanding the masses of the post-supernova remnant of these stars (neutron star or black hole). The ^{12}C$(\alpha,\gamma)^{16}$O reaction is particularly uncertain, due to a complicated resonant reaction mechanism near zero $\alpha + {}^{12}$C energy. This reaction rate can be most directly addressed via stable beam measurements at low energies using a specialized and dedicated facility. It should also be noted that this is a reaction where γ-photon beams can be fruitfully applied to study the inverse reaction. Indirect information is also very helpful for this reaction. For example, measurements of cross sections and angular distributions at higher energies than presently available would be very helpful for constraining the so-called background terms which affect the extrapolation of the cross section to astrophysical energies.

The slow neutron capture process (s process), together with the rapid neutron capture process, are responsible for the synthesis of the majority of elements heavier than iron. The neutron sources for the s process are the $^{13}\mathrm{C}(\alpha, n)$ and $^{22}\mathrm{Ne}(\alpha, n)$ reactions. The thermonuclear reaction rates for these processes are not known for the needed temperatures of $(1-3) \times 10^8$ K, depending on the reaction. These reaction rates are an essential ingredient for a complete understanding of the s process, which must explain the astrophysical sites, neutron densities, and temperatures where this occurs. The most straightforward approach is improved direct measurements, which demand dedicated facilities, with intense beams and low-background detection techniques. Indirect methods are also helpful; for example recent (γ, γ') measurements using photon beams have supplied valuable spectroscopic information that constrains the $^{22}\mathrm{Ne}(\alpha, n)$ reaction.

Near the final stages of the evolution of massive stars, the heavy-ion burning reactions, such as $^{12}\mathrm{C} + {}^{12}\mathrm{C}$ and $^{16}\mathrm{O} + {}^{16}\mathrm{O}$ are responsible for energy generation and nucleosynthesis. The $^{12}\mathrm{C} + {}^{12}\mathrm{C}$ reactions are particularly poorly understood, due to the presence of resonances in the cross section. Improved measurements of this reaction, including charged-particle exit channels, are planned for the future.

Explosive Nucleosynthesis

There is considerable current interest in the nuclear physics associated with explosive events such as novae, x-ray bursts, type Ia supernovae (explosions of white dwarfs), and core-collapse supernovae. Experiments with stable and γ-photon beams contribute in several ways to our understanding of these events. In some cases, the important reactions involve stable isotopes, and thus direct measurements, similar to those discussed in the previous section, are practical. An excellent example of this approach is provided by the $^{17}\mathrm{O}(p, \gamma)^{18}\mathrm{F}$ reaction. Classical novae are thought to be the dominant source of ^{17}O in our galaxy, and this reaction significantly impacts the quantity produced. In Fig. 2, some recent experimental results are displayed along with older data. It is seen that the new results have much smaller error bars and reach significantly lower energies. One attractive aspect of this case is that, due to the higher temperatures involved, it is possible to perform the measurements within the Gamow window. Another example is again the $^{12}\mathrm{C} + {}^{12}\mathrm{C}$ reaction, which also determines the ignition conditions for type Ia supernovae and the ignition of the recently discovered superbursts in accreting binary systems.

Many of the reactions involved in explosive nucleosynthesis involve radioactive nuclei. In these cases, stable beam facilities are able to make significant advances in our understanding using indirect approaches. Most of the reaction rates for $A < 40$ are dominated by a few resonances, making statistical approaches inapplicable. However, it is often possible to measure the spectroscopic properties of the resonant states (excitation energy, spin, parity, and partial widths) using indirect approaches. In favorable cases, the needed reaction rates can be determined with the required precision solely using indirect methods. Many of these reactions will also be studied in the future using radioactive ion beams at large national facilities. The indirect measurements taking place at university facilities are highly complementary to these efforts. The indirect approaches can identify the locations of the resonances with high precision, often with spin and parity information. Thus, the valuable radioactive ion beam time can be devoted to measurements of the strength of resonances at known locations, greatly increasing the efficiency of the process. In addition, some resonances will likely never be possible to measure directly, due to the weak resonance strength, so indirect methods will be the only approach available in some cases.

In novae and x-ray bursts, chains of (p, γ), (p, α), and (α, p) reactions occur on the proton-rich side of the stability line. Transfer reactions on stable targets can often be utilized to probe the relevant resonance states. Excellent energy resolution is often required, due to the relatively close spacing of the levels. The best resolution is typically available using reactions with light projectiles and ejectiles, such as (p, t), (p, n), $(^3\mathrm{He}, d)$, $(^3\mathrm{He}, \mathrm{t})$, and $(^3\mathrm{He}, n)$. In addition, more exotic multi-nucleon transfer reactions, such as $(^{12}\mathrm{C}, {}^{16}\mathrm{C})$ and $(^{12}\mathrm{C}, {}^{6}\mathrm{He})$, can be used to study the structure of nuclei farther off the

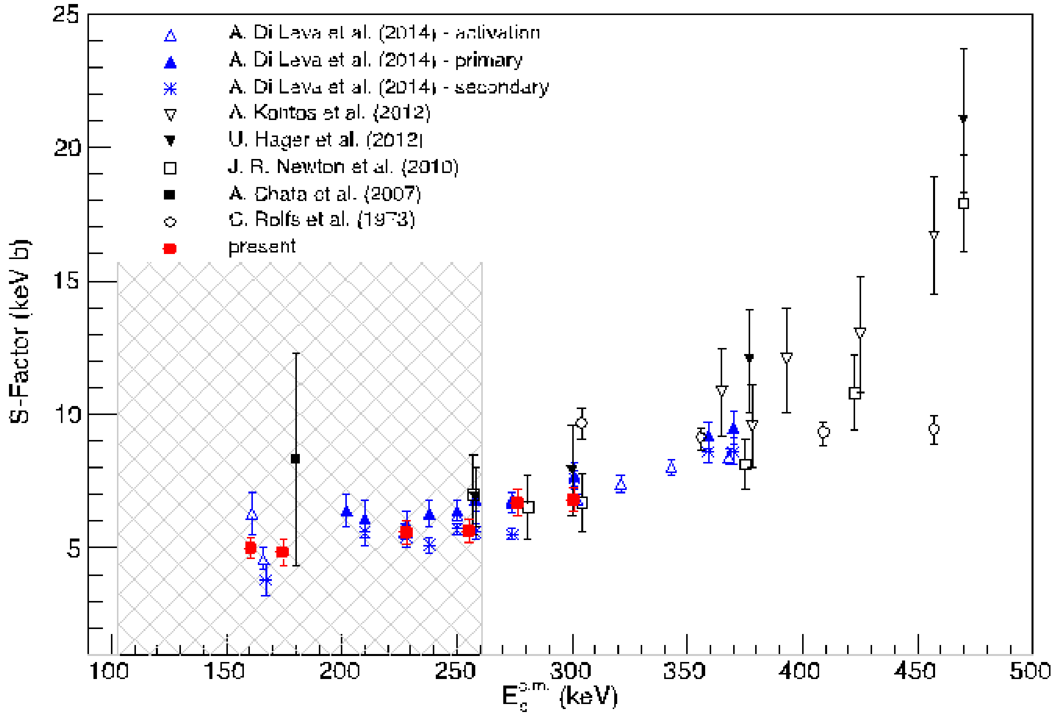


Figure 2: Plot of the world-wide data of the astrophysical S-factor for the $^{17}O(p,\gamma)^{18}F$ reaction as a function of the proton beam energy in the c.m. system. The solid red circles are the new data from the LENA facility at TUNL and the hashed area is the Gamow window.

stability line, which is applicable for reactions occurring in x-ray bursts. Also, the proton transfer reactions (^{3}He$,d)$ and (d,n) are of special interest as they can supply information about the proton widths of resonances using well-established transfer reaction theory. It should be noted that indirect techniques are not limited to resonances but can also be used to study non-resonance cross sections; the Asymptotic Normalization Coefficient (ANC) method or the Trojan Horse Method (THM) are two implementations in this case. Two particularly compelling cases of resonant reactions where indirect techniques are being utilized are studies of the ^{18}F$(p,\alpha)^{15}$O reaction (involving states in ^{19}Ne) and the ^{25}Al$(p,\gamma)^{26}$Si reaction (involving states in ^{26}Si).

2.2 Direct Measurements

Specialized Facilities: *At TUNL-LENA and University of Notre Dame:*
This experimental program in nuclear astrophysics

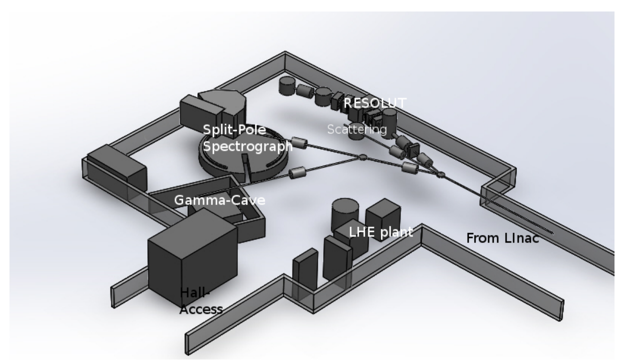


Figure 3: The planned reconfiguration of the FSU experimental hall with the Enge split-pole spectrograph.

requires specialized and dedicated facilities. For direct measurements, high beam currents, efficient and low-background detection methods, and long running times are required. Backgrounds can be reduced by utilizing pulsed beams, ultra-pure targets, passive and active shielding, coincident detection techniques, and/or by performing the measurements deep underground. The existing Laboratory for Experimental Nuclear Astrophysics (LENA) at TUNL is presently performing such measurements with normal kinematics and is planning an upgrade which will increase the available beam intensity. An underground accelerator, called CASPAR, is presently being developed at the University of Notre Dame. This facility plans to study the s-process neutron source reactions, which are cases where the background reduction coming from being underground is particularly compelling. Another approach to direct measurements is inverse kinematics, where a heavy ion beam bombards a gas target of hydrogen or helium and the heavy reaction products are detected in a recoil separator. The recently-completed heavy-ion accelerator and recoil separator (St. Ana and St. George) at the Notre Dame Nuclear Science Laboratory (NSL) is an example of this approach, which is designed to measure alpha induced reaction processes of relevance for late stellar burning scenarios using inverse kinematics techniques.

pp-reactions: *At University of Notre Dame*
Critical measurements for reducing the uncertainty in the $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$ reaction have been performed at Notre Dame. The experimental results allow a self-consistent r-matrix simulation of the entire cross section curve, which translates into a more reliable extrapolation of the experimental data in the solar energy range and limits the uncertainties in the production rate of the solar neutrinos from the second and third pp-chain. Future efforts at Notre Dame will focus on the study of proton capture reactions on lithium isotopes which still suffer from substantial uncertainties in the low energy range.

CNO reactions: *At University of Notre Dame and TUNL-LENA:*
The CNO cycle in the sun is of limited relevance for the solar energy budget but it may provide a new and independent measure of the solar core metallicity through the analysis of the CNO neutrinos at Borexino and other neutrino detectors. This requires an improved understanding of the low energy reaction cross sections of the CNO reactions. The Notre Dame group has systematically studied the radiative capture processes that lead to the production of CNO neutrinos through the β decay of the reaction product such as $^{14}\mathrm{N}(\mathrm{p},\gamma)^{15}\mathrm{O}$, $^{15}\mathrm{N}(\mathrm{p},\gamma)^{16}\mathrm{O}$, and $^{17}\mathrm{O}(\mathrm{p},\gamma)^{18}\mathrm{F}$. The measurements were performed over a wide energy range and were complemented by an extensive set of elastic scattering experiments. A multi-channel multi-level R-matrix has been developed to analyze all the data, taking into account the new measurements as well as existing data for all reaction channels has been performed for all these processes. The results demonstrate in some cases substantial deviations to long-accepted values for low energy extrapolation.

These studies are being expanded to the measurement of $^{12}\mathrm{C}(\mathrm{p},\gamma)1$ and $^{16}\mathrm{O}(\mathrm{p},\mathrm{g}\gamma$ to study the contribution of $^{13}\mathrm{N}$ and $^{17}\mathrm{F}$ decay neutrinos to the solar CNO neutrino flux.

NeNa reactions: *At University of Notre Dame and TUNL-LENA:*
The NeNa cycles play a role in shell hydrogen burning of massive stars and in explosive nova events that correspond to thermonuclear runaways at the surface of accreting white dwarfs. The Notre Dame group reinvestigated the slow $^{20}\mathrm{Ne}(\mathrm{p},\gamma$ reaction and the possible contribution of a subthreshold state in the $^{21}\mathrm{Na}$ compound nucleus. This reaction determines the cycle period for the NeNa cycle.

At the LENA facility at TUNL, the $^{23}\mathrm{Na}(\mathrm{p},\alpha)$ has been measured using the high intensity ECR platform.

HI fusion *At Florida State University, with a group from Indiana University, at University of Notre Dame, at Texas A&M University*
Fusion reactions between carbon and oxygen isotopes dictate the fate of the star during its last burning phases. Heavy ion fusion experiments at ANL have indicated a possible hindrance mechanism that reduces the fusion probability at very low energies. These energies are only available at university accelerator facilities. A number of stellar fusion reaction studies such as $^{12}\mathrm{C}+{}^{12}\mathrm{C}$, $^{12}\mathrm{C}+{}^{13}\mathrm{C}$ and $^{12}\mathrm{C}+{}^{16}\mathrm{O}$ are being pursued at Notre Dame. Complementary transfer reactions for probing the $^{12}\mathrm{C}$ cluster structure in the compound nuclei have been and are being measured at FSU and Texas A&M.

2.3 Indirect Methods

At the University of Notre Dame, at Ohio Univer-

sity, at TUNL-HIγS, at Florida State University

The Notre Dame group introduced a program for mapping critical resonant states for reactions in the αp-reaction path using (p,t) and (^{4}He,^{8}He) reactions at the Grand Raiden Spectrometer at RCNP Osaka. The program was completed, mapping the entire αp-process from ^{18}Ne to ^{48}Cr and a complete set of resonance data is now available for direct measurement at radioactive beam facilities such as CARIBU using the HELIOS detector, or at ReA3 using ANASEN. The Grand Raiden experiments were complemented by (^{3}He,n) reaction studies at the Notre Dame tandem accelerator using the time of flight techniques for neutron spectroscopy and measuring the decay channels of the populated resonance states. The TwinSol facility was modified to serve as a medium-resolution spectrometer to determine the strength of break-out reactions such as $^{15}\mathrm{O}(\alpha,\gamma)^{19}$Ne from the hot CNO cycles by using coincidence techniques between $^{19}\mathrm{F}(^3\mathrm{He},\mathrm{t})^{19}$Ne transfer reactions and subsequent α and γ decay products. This method is presently being refined by converting TwinSol into a HELIOS type spectrometer device to increase the efficiency of transfer reaction studies.

The above example shows the power of indirect methods and stable ion beams, relying upon specialized detection systems. In the case of charged-particle reaction products, the best resolution is provided by magnetic spectrometers, a capability which is presently lacking in North America. However, two laboratories have plans to rectify this situation; the John D. Fox Accelerator Laboratory at Florida State University (FSU) is planning to install the Enge split-pole spectrograph that was previous utilized at Yale University and TUNL is planning to upgrade and refurbish their Enge split-pole spectrograph. The planned configuration the split pole at FSU is shown in Fig. 3. For the cases of neutrons in the final state, high-resolution neutron spectroscopy is carried out using pulsed beams and long flight paths at Ohio Universitys Edwards Accelerator Laboratory.

Photon beams are becoming increasingly important for nuclear astrophysics. The High-Intensity γ-ray Source (HIγS) at TUNL provides quasi-monoenergetic γ-photon beams that can be utilized to bombard suitable samples. Direct measurements of radiative capture cross sections can be obtained by measuring the reverse reaction and applying the reciprocity theorem. An excellent example is the $^{16}\mathrm{O}(\gamma,\alpha)^{12}$C reaction, which can be studied to determine the $^{12}\mathrm{C}(\alpha,\gamma)^{16}$O cross section. In addition, nuclear resonance fluorescence, i.e., the (γ,γ') reaction, can be utilized to locate potential resonances and determine their quantum numbers.

2.4 In-flight Radioactive Beam Experiments: TWIN-SOL and RESOLUT

At University of Notre Dame and Florida State University

The university laboratories at Notre Dame and Florida State University have developed in-flight radioactive beam capabilities.

TwinSol is a facility for producing beams of light radioactive ions at energies near the Coulomb barrier. Commissioned in 1998, it is one of the first instruments to produce intense radioactive beams in this energy region. Seven Physical Review Letters and over 50 other papers in refereed journals have so far been published based on research done with TwinSol. One of the early PRLs was the subject of a short article in the CERN Courier, and several of the papers have received 150 or more citations. A collaboration between the University of Notre Dame and the University of Michigan, TwinSol also has an active national and international user community.

The most recent work with TwinSol has utilized novel detectors, such as the prototype active-target time projection chamber (pTPC) developed at Michigan State University, and deuterated liquid scintillators that produce a neutron energy spectrum without the need for time-of-flight measurements. The neutron detectors were recently used to study (d,n) reactions on ^{7}Be and ^{17}F.

The pTPC has been used to study proton and alpha-particle elastic and inelastic scattering from radioactive nuclei, to measure an entire near- and sub-barrier fusion excitation function at a rate of only 100 particles per second, and to investigate the angular correlation of alpha particles from the decay of the Hoyle state by visualizing their tracks. Planned future experimental programs with this device include the study of charged-particle-induced transfer reactions in inverse kinematic using ^{1}H , ^{2}H and ^{4}He targets.

Florida State University has been operating the RESOLUT in-flight radioactive beam facility since 2006. This facility, like TwinSol, uses two superconducting solenoids to focus reaction products onto a secondary target, but uses in addition a superconducting RF resonator and a large-acceptance magnetic spectrometer to sharpen the beam energy and select the beam isotopes more cleanly. RESOLUT has recently been used to perform a series of (d,n) transfer reactions to study the resonance spectrum for (p,γ) reactions, an indirect technique which can supply information about the partial proton widths, in addition to the excitation energy, spin, and parity. RESOLUT has also been used to measure proton and α–resonance scattering using the new ANASEN active–target detector, see also 2.7. ANASEN will be used at RESOLUT and ReA3 to measure excitation function cross sections of (α, p) reactions with the aim of calibrating the astrophysical reaction rates of the αp process.

2.5 Neutron Source Reactions

At University of Notre Dame and TUNL-HIγS

The identification and understanding of stellar neutron sources and neutron poisons is critical for a reliable model description of the s-process which is responsible for the production of about 50% of the heavy elements. The s-process is a major signature for mapping and understanding the chemical evolution of our universe through the chemical analysis of meteoritic inclusions. Both direct and indirect measurement techniques can be profitably applied to the neutron source reactions.

There has been a combined effort by the UNC and ND groups using the HIγS facility at TUNL to understand critical resonance states in $^{22}\mathrm{Ne}(\alpha, \mathrm{n})$ neutron source through $^{26}\mathrm{Mg}(\gamma, \gamma')$ nuclear resonance fluorescence measurements.

Direct measurements are planned using inverse kinematic techniques at the Notre Dame St. George separator and forward kinematics at the future CASPAR underground accelerator facility. Direct measurements have already been performed at Notre Dame on the $^{17}\mathrm{O}/^{18}\mathrm{O}(\alpha, \mathrm{n})$ as well as on the $^{25}\mathrm{Mg}/^{26}\mathrm{Mg}(\alpha, \mathrm{n})$ reactions, which showed substantial differences from tabulated results that have so far been used in s-process site simulations.

2.6 Unambiguous Identification of the Second 2^+ State in ^{12}C

At TUNL-HIγS

Late-stage red giant stars produce energy in their interiors via helium (α) burning. The outcome of helium burning in red giant stars is the formation of the two elements: carbon and oxygen. The ratio of carbon to oxygen at the end of helium burning has been identified as one of the key open questions in nuclear astrophysics. Helium burning proceeds through the 3α process to produce carbon, which eventually burns to oxygen via the $^{12}\mathrm{C}(\alpha, \gamma)^{16}\mathrm{O}$ reaction.

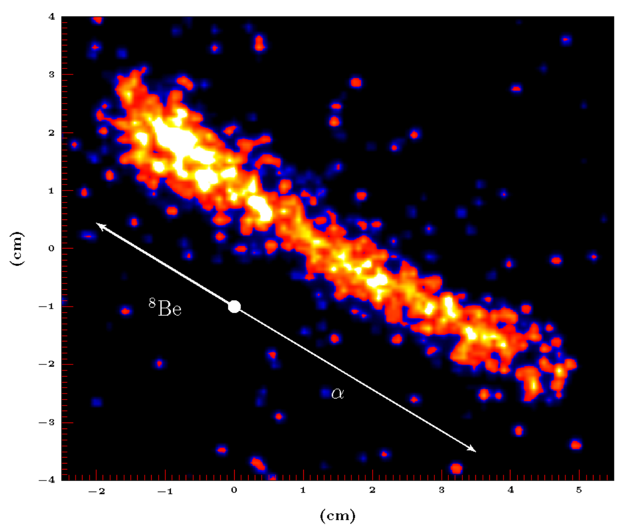


Figure 4: Typical image of three alpha particles detected recorded in the the optical time-projection chamber from the reaction $^{12}\mathrm{C}(\gamma, \alpha_0),^{8}\mathrm{Be}(\rightarrow \alpha + \alpha)$. Both α–products of the ^{8}Be-decay are contained in the top-left track.

An excited 0^+ state in ^{12}C, named the Hoyle State after Fred Hoyle who predicted its existence, plays a central role in determining the rate of the 3α process. This prediction was the first and quite possibly still the best example of an application of the anthropic principle in physics. Soon after the discovery of this excited state in ^{12}C, predictions of the rotational band structure of the Hoyle state led to a fifty-year search for an excited state built upon the Hoyle state. An excited state having the properties of the Hoyle state excitation was unambiguously identified at the HIγS laboratory TUNL and was reported in a letter publication. The state was identified using the ^{12}C$(\gamma,\alpha)^{8}$Be reaction. The alpha particles produced by the photodisintegration of ^{12}C were detected using an optical time projection chamber (OTPC). Data were collected at beam energies between 9.1 and 10.7 MeV using the intense nearly monoenergetic γ-photon beams at the HIγS facility. The measured angular distributions determine the cross sections and the E1-E2 relative phases as a function of energy leading to an unambiguous identification of the second 2^+ state in ^{12}C at 10.13(60) MeV. This work was a collaborative effort which includes TUNL, the University of Connecticut, Yale University, Physikalisch-Technische Bundesanstalt, Germany, and the Weizmann Institute of Science, Israel. In Figure 4, a γ ray of 9.5 million electron-volts (MeV) (not seen in the image) breaks apart a carbon nucleus into a helium fragment and a ^{8}Be fragment. The ^{8}Be immediately decays into two α particles and appears as two tracks merged into each other. A fast, high-resolution, and image intensified camera creates this image. Other components of the OTPC gather information on the energy of these fragments and the angles at which they are ejected to provide a complete picture of this reaction.

W.R. Zimmerman, M.W. Ahmed, B. Bromberger, S.C. Stave, A. Breskin, V. Dangendorf, Th. Delbar, M. Gai, S.S. Henshaw, J.M. Mueller, C. Sun, K. Tittelmeier, H.R. Weller, and Y.K. Wu *Unambiguous Identification of the Second 2^+ State in C^{12} and the Structure of the Hoyle State* Physical Review Letters, 110, 152502 (2013).

2.7 Detector and Method Development: ANASEN

At Florida State University, with groups from Louisiana State University and Texas A&M University

The Array for Nuclear Astrophysics Studies with Exotic Nuclei (ANASEN) is a charged-particle detector array developed specifically for experiments with radioactive ion beams, primarily to measure the nuclear reactions important in stellar explosions. ANASEN is a collaborative project between scientists at Louisiana State University, Florida State University (FSU) and Texas A&M University. ANASEN was constructed and commissioned at the FSU accelerator laboratory, using more than 12 weeks of beam-time. The completed array has been in operation since Summer 2012, performing measurements with beams of radioactive ions from the RESOLUT facility at FSU. ANASEN was also used in the commissioning exotic beam experiment at the new ReA3 facility of the National Superconducting Cyclotron Laboratory of Michigan State, measuring the elastic proton scattering from a beam of ^{37}K.

ANASEN is a universal device that can be used in active target mode (target gas serving as an active medium for tracking detectors) and also in solid target mode. ANASEN has three major components: An array of resistive strip and double-sided silicon strip (DSSD) detectors, backed by an array of CsI(Tl) scintillators with PIN-diode readout. The active target is realized through a position-sensitive proportional counter of more than 40 cm active length. The readout is performed by Application Specific Integrated Circuits (ASICs) coupled with conventional electronics. A schematic representation of ANASEN is shown in Fig. 5. ANASEN has cylindrical geometry around the beam axis, with a proportional counter and silicon barrel array arranged as concentric cylinders. A photo of the components is shown in Fig. 6

The ANASEN active target detector system (see sect. 2.7) will be used to create a very sensitive system to study transfer reactions of the (d,p) type. ANASEN can operate with an effective target thickness of ≈ 2 mg/cm^2, without losing substantially in resolution, which is more than a factor ten increase in luminosity over fixed targets of deuterated polyethylene.

ANASEN will be used as a traveling device, performing experiments and developing its capabilities at the FSU radioactive beam facility RESOLUT and delivering a very high sensitivity for the most exotic beams available at the re-accelerated beam programs of the NSCL and FRIB.

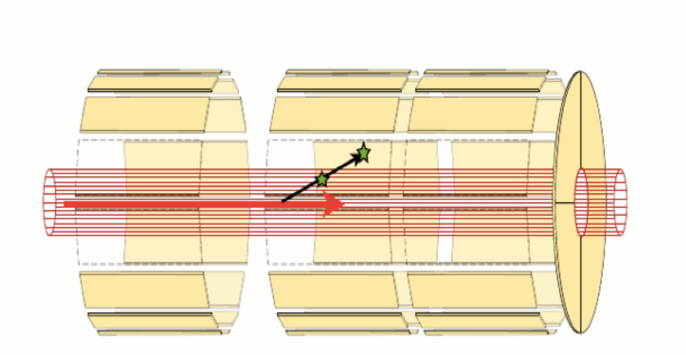


Figure 5: Schematic representation of ANASEN. The beam enters from the left, proceeding through the gas-filled chamber. Light charged particles are tracked through the position-sensitive proportional counter and silicon detectors.

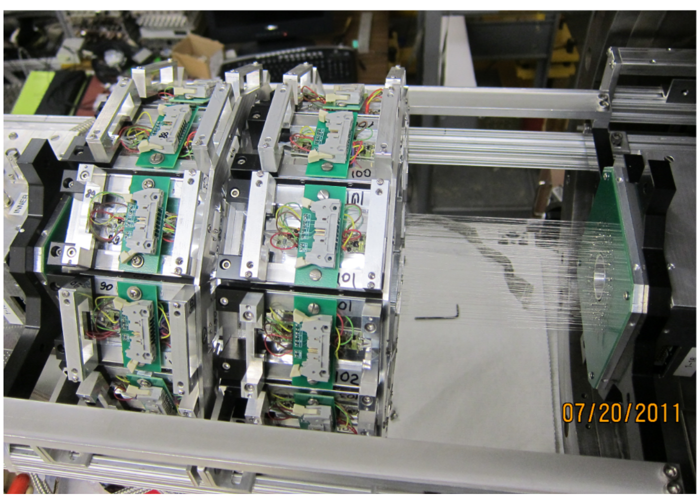


Figure 6: ANASEN being prepared for experiments. Two rings of Silicon-CsI detector rings surround the multi-wire proportional counter.

3 The Scientific Impact of ARUNA: Nuclear Structure and Reactions

Today's experiments in low energy nuclear science are characterized by a diversity of experimental methods. Some experimental programs described in the next sections are based on unique experimental capabilities available at ARUNA laboratories, such a mono-energetic neutron or γ–photon beams. Even in the coming era of FRIB, the big questions of the field will be studied in the context of individual nuclides and a variety of methods, requiring individually optimized experimental setups. The energy range and diversity of the experiments envisioned for the re-accelerated beam program at FRIB is commensurate with many of the ARUNA laboratories, which makes them ideal places to develop new experimental equipment and methods.

The area of nuclear structure and nuclear reactions examine the complexity of the nuclear many-body problem and how its properties can be understood from first principles. In the past decade, the topics of nuclear structure and nuclear reactions have become understood as two closely related aspects of the same scientific topic, a development that is represented within the programs of ARUNA laboratories described below. These coupled research areas are the foundation for the many applications of nuclear physics, especially in the context of astrophysics, which was described in Section 2. These topics were summarized as the following "big questions" of nuclear science in the 2007 Nuclear Science and Nuclear Astrophysics White Paper, which are quoted to introduce the following paragraphs and sections.

How does shell structure evolve with neutron number ?

How do NNN forces impact structure and reaction properties of nuclei ?

Many features of near-stable nuclei relate to the concept of "single-particle orbits" that group to form closed shells at certain "magic" numbers of neutrons and protons. These shells arise naturally in a mean-field picture and are due to energy gaps between the single-particle orbits. A central question is how shell closures along these so-called magic numbers are modified in the presence of a large neutron excess.

While the forces between pairs of protons and neutrons are relatively well known and were summarized as nucleon-nucleon (NN) potentials, the same cannot be said for the forces between larger groups of nucleons. Recent results in theoretical nuclear science show that the experimental properties of light nuclei cannot be entirely derived from the known NN potentials alone. The presence of three-body forces, or NNN potentials, manifests itself in the stability of light "Borromean" nuclei like ^{6,8}He, ^{9}Be, and ^{11}Li. Studies at ARUNA laboratories relating to the topic of the relation of the nuclear mean field to the fundamental nucleonic interactions are described in Sections 3.1 and 3.4.

What is the impact of the continuum on nuclear properties?

As we probe exotic nuclei near the neutron drip line, the neutron separation energy decreases, and the role of open channels increases. A consistent description of the interplay between scattering states, resonances and bound states in a weakly-bound nucleus requires an "open quantum system" formulation of the many-body problem, such as the continuum extension of the nuclear shell model. There are many examples of the impact of many body correlations and continuum coupling on the structural properties of neutron-rich nuclei. Nuclear halos with their low-energy decay thresholds and cluster structures are obvious examples. This convergence of nuclear reaction methods with nuclear structure theory, the communication between the inside and outside of the nuclear system, will be a central theme of nuclear science in the coming decade. ARUNA laboratories are pursuing research programs on the physics of open quantum systems, as described in Sect.3.2.

What is the origin of simple patterns in complex nuclei?

One overarching theme in nuclear science is the emergence of collective, coherent phenomena out of the inherent complexity of the nuclear multi-particle system. Collective modes like vibrations and rotations are common examples. Often, such simple patterns reflect underlying symmetries of the many-body system. For instance, the collective excitations of the proton-neutron system are an expression of the underlying isospin-symmetry of the nuclear interaction. As the interest of nuclear structure science is focused on nuclei with very large neutron excess, such proton-neutron excitations can be used to investigate the resulting changes in the collective wave functions. Research on the emergence of simple patterns is described in Sections 3.5 and 3.6.

What is the equation of state (EOS) of nuclear and neutron matter?

The bulk properties of nuclear systems play a key role in several areas of physics. Of obvious importance is the equation of state of nuclear and neutron matter, which governs the properties of neutron stars, plays an important role in core-collapse supernovae, and may be measurable in intermediate-energy heavy-ion collisions. At present, large uncertainties in the pairing interaction and the bulk symmetry energy lead to substantially unconstrained descriptions of neutron matter. From a purely microscopic point of view, it remains an open question if ab initio based calculations can be performed for neutron matter with NNN interactions. Also, basic questions about the EOS above saturation density remain open, since non-relativistic descriptions in terms of neutrons and protons are expected to break down at a certain point. As a result, threshold densities for the appearance of strange baryons and/or partially deconfined quarks, their effect on the EOS, and the consequences for neutron star and supernova models, need to be understood. Investigations of the bulk properties of nuclear matter are described in Section 3.10.

In the area of nuclear structure and reaction physics, the ARUNA laboratories pursue the same scientific goals as the national community and are often tightly linked to programs at national user facilities. In the following, examples of results from ARUNA laboratories pursuing the above listed topics are given and their plans for near-future projects described.

3.1 Investigation of the Nucleon-Nucleon Force: First Measurements of Spin-Dependent Cross Sections for the Photodisintegration of ^{3}He

At TUNL-HIγS

Determination of the nucleon-nucleon force is at the very basis of developing a comprehensive theory of the atomic nucleus. To this end, experiments establishing direct observables for few-nucleon dynamics are essential for advancing ab initio nuclear reaction and structure calculations. Recently, the double polarization (polarized beam and polarized target) cross section for photodisintegration of ^{3}He was measured at HIγS for the first time.

These new data provide stringent tests of state-of-the-art three-nucleon calculations that use realistic nucleon-nucleon and three-nucleon interactions. The measurements were performed at 12.8 and 14.7 MeV using a ^{3}He target polarized by the spin-exchange optical pumping technique and the circularly polarized mono-energetic gamma-ray beam at HIγS. The measured spin-dependent double-differential cross sections are compared to state-of-the-art three-body calculations in Figure 7. The good agreement between the data and calculations gives confidence in the theoretical treatment of this reaction. Furthermore, these data are used to determine the integrand for the Gerasimov-Drell-Hearn (GDH) sum rule for ^{3}He which relates the dynamics of the photoabsorption process to the static magnetic moment of the nucleus.

This work was published in G. Laskaris et al., Phys. Rev. Lett. 110, 202501 (2013).

TUNL is developing a new program to measure precision data on the neutron-neutron quasi-free scattering and search for the di-neutron bound state by studying the γ–induced $\gamma+t \rightarrow n+n+p$ breakup of tritium.

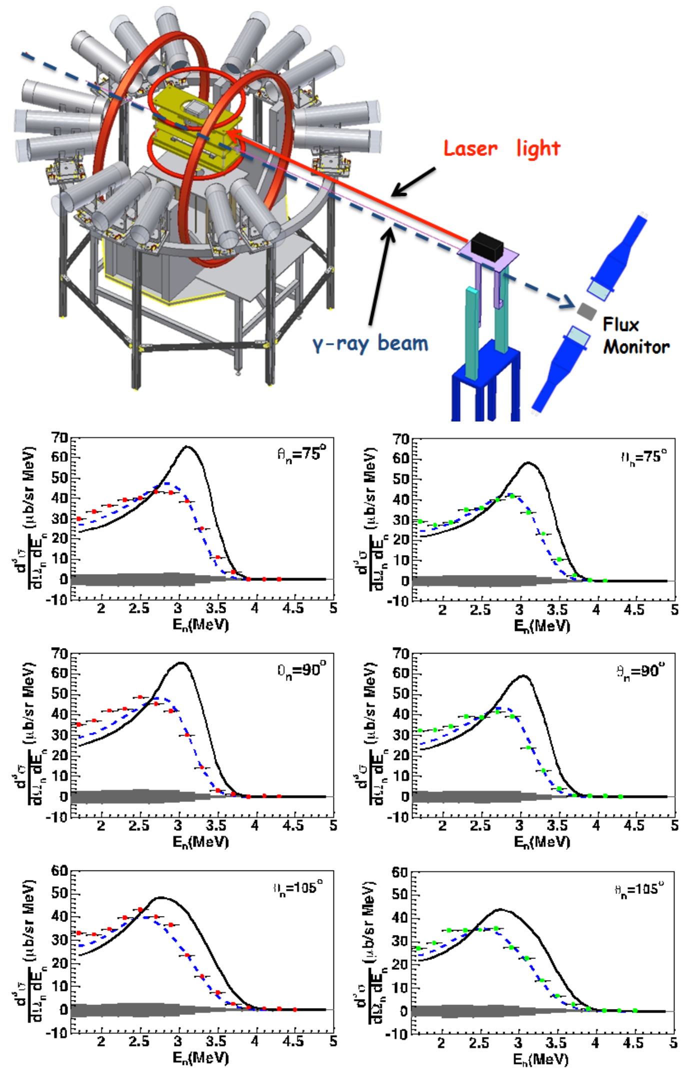


Figure 7: (Top) Schematic of the experimental apparatus: The movable ^{3}He target system is surrounded by 16 liquid scintillator detectors.(Bottom) Spin-dependent double-differential cross sections for parallel (left panel) and anti-parallel (right panel) states as a function of the neutron energy. The data are compared with two theoretical calculations made with (dashed curves) and without (solid curves) the Coulomb interaction. The band at the bottom shows the systematic uncertainties.

3.2 Nuclei as Open Systems – Super-radiance in Competing Decay Channels

At Florida State University, with a group from

Louisiana State University

A new research program at FSU is designed to study the presence of the super-radiant or doorway-state mechanism in the presence of competing particle-decay channels. The phenomenon of super-radiance is based on the mixing interaction of multiple unbound quantum states through the continuum part of their wave functions, which in effect concentrates the respective decay strength in one state. The effect is based on a general mechanism and has been studied in the context of quantum optics, atomic and nuclear scattering.

An interesting facet of the super-radiant mechanism for the stability of exotic nuclei is the presence of multiple, competing particle-decay channels. It can be speculated that the mechanism of super-radiance will, in effect, separate neutron– from α–resonances in the spectrum.

In the coming years, the details of the super-radiance effect in nuclei will be studied using the new split-pole spectrograph setup at the FSU laboratory (see also Sect.2.3), in conjunction with neutron detectors and a silicon-detector array. The mechanism of super-radiance is a natural ingredient of the continuum shell model, which has been successfully applied to sd-shell nuclei.

3.3 Cross-shell Excitations Investigated by γ–Spectroscopy

At Florida State University

The shell model using the USD, USD-A, and USD-B interactions provides the best description of the positive-parity excitations of the shell orbits over a wide range of nuclei between ^{16}O and ^{40}Ca. A group at the FSU laboratory is studying a range of moderately exotic nuclei between mass 20 and 40 through γ–ray spectroscopy. The experiments have established a set of negative-parity cross-shell intruder excitations, which was used to test different cross-shell interactions of the shell-model. The WBP-a interaction describes one-particle-one-hole cross-shell excitations quite well, but does not agree with some other states, which presumably involve either multi-particle-multi-hole states or excitations across more than one shell.

A wider range of moderately neutron-rich nuclei will be investigated in the coming years at FSU, with the goal of anchoring the spectrum of cross-shell excitations, which also determine the properties of exotic nuclei. This research program is directly connected to studies of exotic nuclei at the NSCL and at Argonne National Laboratory, using the SEGA, Gammasphere and GRETINA γ-ray detector arrays.

3.4 Shell-Modification Studies using Transfer Reactions on Radioactive Beams

At Florida State University, with a group from Louisiana State University

The modification of shell structure at the limits of nuclear binding and interaction with the continuum of unbound states will gain center stage at FRIB. The excitations of neutrons in particular can be expected to deviate from the behavior found in ordinary nuclei, as they are solely confined by the strong force. As an example, the location of the neutron drip-line in ^{24}O has been attributed to the presence of three-body forces, which raise the neutron $d_{3/2}$ orbital to be unbound and influence the excitation spectra of less exotic isotopes.

The experimental methods required for such studies are being developed today and are already being used in experiments at ARUNA laboratories, and the re-accelerated RIB facility ReA3. The spectrum of bound states in ^{20}O was studied at Argonne National Lab with HELIOS, establishing good agreement of the experimental data with the wave functions predicted by the phenomenological USD-A and USD-B shell-model interactions, while the $d_{3/2}$ strength is almost entirely expected to be unbound. The ANASEN detector (see Sect.2.7) is being developed by this group as a highly efficient spectrometer for (d,p) reactions on exotic nuclei, with the aim to establish the systematic behavior of the $d_{3/2}$ strength in moderately neutron-rich nuclei of the sd shell. The development of neutron-resonance spectroscopy through the (d,p) reaction at the FSU accelerator laboratory aims at a program investigating the shell structure of exotic nuclei with ReA3 and

FRIB.

3.5 Microscopic Origin of Deformation Coexistence

At Florida State University

The high-spin structure of nuclei in the f-p-g shell ($28 \leq$ N,Z ≤ 50) has been studied for its rich spectrum of well formed rotational bands and exhibits coexistence of prolate and oblate deformations. A renewed interest in nuclei of this mass region comes from the vastly increased capability of large-space shell-model calculations.

In exploratory calculations, several rotational bands are predicted, as a result of microscopic predictions. Many other characteristics can also be inferred from the wave functions with the addition of small amounts of additional code. The promising ability to achieve a better understanding of the microscopic structure of apparently collective rotational bands will strongly motivate further experimental study and will be a future focus of the γ–ray spectroscopy program at FSU.

3.6 "Scissors Mode", Mixed-Symmetry States and Multi-Phonon Excitations

At University of Kentucky, and at TUNL-HIγS

The lowest collective nuclear excitations with proton-neutron degrees of freedom are the so-called mixed-symmetry states, which contain both proton-neutron symmetric, and proton-neutron anti-symmetric components in their wave-functions. In these excitations, the isovector character is thought to be limited to the valence nucleons only. These excitations, characterized by their enhanced M1 decays, lie between 2 and 3 MeV (see Fig.8) and have been established in many medium-mass and heavy nuclei, most prominently through nuclear resonance fluorescence studies of the 1^+ "scissors mode".

An active research program into these excitations is pursued at the TUNL-HIγS facility, which delivers the worlds most intense mono-energetic, tunable γ-photon beam, produced by inverse Compton-scattering of photons from a free-electron laser. The photon beam is used to selectively excite collective 1^+ and 1^- states and observe their decay through high-resolution γ-ray spectroscopy. The capability to produce polarized beams and the direct electromagnetic excitation mechanism makes these studies very sensitive, selective, and of high precision in the measurement of ground-state electromagnetic matrix elements.

A complementary technique of inelastic neutron-scattering is used at the University of Kentucky Accelerator Laboratory (UKAL), taking advantage of mono-energetic, tunable neutrons, which are produced by intense proton and deuteron beams on gaseous deuterium and tritium targets. The inelastic neutron scattering reaction generally excites levels with spins up to I=6 at energies up to the incident neutron energy. Their decays can be observed using high-resolution γ–ray spectroscopy. The decay lifetimes are measured through Doppler-shift methods and γ–ray multipolarities are determined through angular distribution measurements. This method has proven to be well suited to study the spectrum of 2^+ states of mixed-symmetry character, as well as multi-phonon states.

The UKAL group has recently performed a series of measurements with solid, isotopically enriched XeF_2 targets, which were used in experiments at both UKAL and HIγS, filling an important gap in nuclear structure information of these nuclides and studying nuclear excitations with potential impact on neutrinoless double–β decay studies, described in Section 3.8.

3.7 Fine Structure of the Giant M1 Resonance in ^{90}Zr

At TUNL-HIγS

Understanding the magnetic dipole and Gamow-Teller responses in nuclei are long-standing challenges in nuclear physics. Because of the close relationship between the M1 excitation and neutrino-nucleus processes, knowledge of the M1 excitation is particularly important for the estimate of neutral-current cross sections in supernova explosions and terrestrial detection of supernova neutrinos.

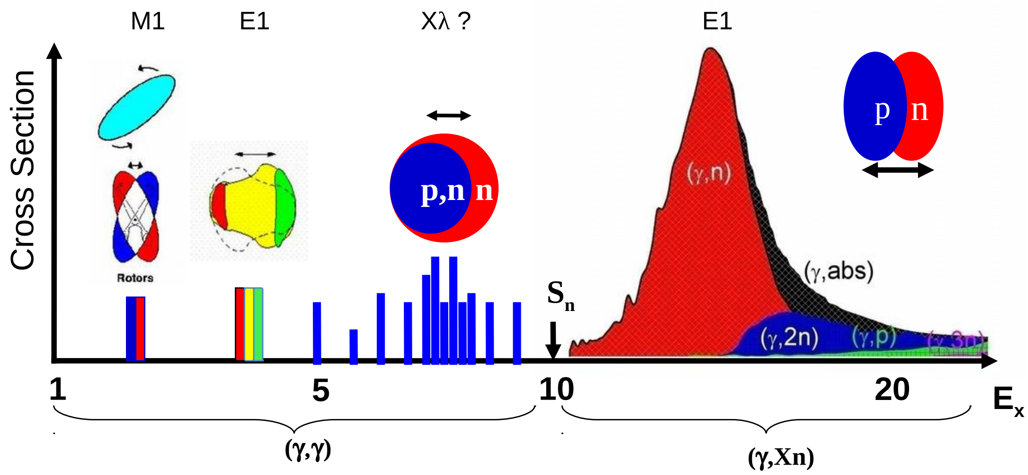


Figure 8: Schematic representation of collective nuclear excitations studied by real photon probes. The "scissors mode" around 2..3 MeV, two-phonon excitations around 4 MeV, the "pygmy" dipole resonance around 5-10 MeV and the giant dipole resonance above 10 MeV.

As a general observation, measurements find considerably less magnetic strength than theoretically expected. This is known as the "quenching" phenomenon of the nuclear spin-flip magnetic response. Explaining the dynamics of quenching means understanding the coupling of the two-quasiparticle doorway states to many-quasiparticle configurations. The M1 excitations in ^{90}Zr were studied in a photon-scattering experiment with mono-energetic and 100% linearly polarized photon beams from 7 to 11 MeV. The results of the experiment are displayed in Fig.9. More than 40 1^+ states were identified from observed ground-state transitions, revealing the fine structure of the giant M1 resonance for the first time. The concentration of M1 strength around 9 MeV is further confirmed in three-phonon quasiphonon model calculations and explained as fragmented spin-flip excitations. The observed strongly fragmented M1 strength and its absolute value can be explained only if excitations more complex than the single particle-hole excitations are taken into account. The theoretical investigations of the fragmentation pattern of the M1 strength indicate a strong increase of the contribution of the orbital part of the magnetic moment due to coupling of multiphononon states. The effect is estimated to account for about 22% of the total M1 strength below threshold.

This work was published in G. Rusev, N. Tsoneva, F. Dönau, S. Frauendorf, A. S. Adekola, S. L. Hammond, C. Huibregtse, J. H. Kelley, E. Kwan, H. Lenske, R. Schwengner, A. P. Tonchev, W. Tornow, and A. Wagner. Phys. Rev. Lett. 110, 022503 (2013).

3.8 Nuclear Structure Studies for $0\nu\beta\beta$ Decay

At TUNL-HIγS, University of Kentucky

A research program using multiple instruments at TUNL is in progress to study the nuclear physics context of neutrinoless double–β decay ($0\nu\beta\beta$). Quasiparticle random phase approximation (QRPA) theory is used to calculate the matrix elements of $0\nu\beta\beta$ decays. The validity of such calculations is tested by measuring the fragmentation of the pygmy dipole strength using nuclear resonance fluorescence spectroscopy in mass 40-150 nuclides. A new program has been initiated at the TUNL tandem laboratory with the aim to study the same decay matrix elements through the $(^3\mathrm{He}, \mathrm{n})$ reaction, measuring neutron time-of-flight with a pulsed ^{3}He beam. The studies, which connect the same initial and final states as the $0\nu\beta\beta$ decay include $^{76}\mathrm{Ge}(^3\mathrm{He}, \mathrm{n})^{76}\mathrm{Se}$ and similar experiments on ^{74}Ge, ^{74}Se, ^{76}Se, ^{126}Te, ^{128}Te,^{130}Te,^{132}Xe,^{134}Xe, ^{136}Xe.

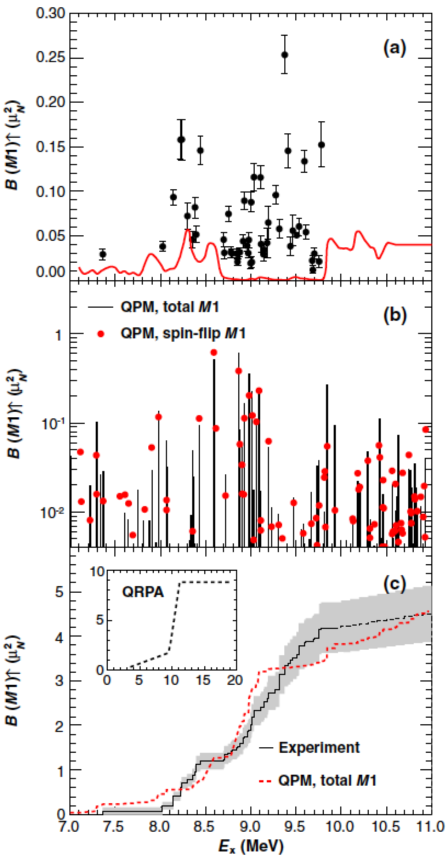


Figure 9: Results for (a) the measured B(M1) strength of discrete levels in ^{90}Zr compared with the detection limits (red solid line) and (b) predictions from the quasiparticle phonon model. A comparison of the measured and calculated QPM cumulative M1 strength is shown in panel (c). The shaded area gives the uncertainty of the experimental values.

Another study at the University of Kentucky is aimed at characterizing background signals in neutrinoless double–β decay experiments. The University of Kentucky Van de Graaff accelerator was used to produce fast, mono-energetic neutrons to measure γ-ray spectra following $(n, n'\gamma)$ reactions on ^{76}Ge, ^{134}Xe and ^{136}Xe, which may create neutron-induced background signals in $0\nu\beta\beta$ experiments. In ^{76}Ge, two excited states were identified, which decay by the emission γ-rays, within the detector resolution of the $0\nu\beta\beta$ Q-value. A similar result was obtained in ^{134}Xe, where a 2485-keV γ ray could create background signals for the EXO experiment, which contains 20% of ^{134}Xe in its liquid xenon TPC detector.

3.9 Statistical Nuclear Physics

At Ohio University and University of Notre-Dame

Hauser-Feshbach (HF) theory of compound nuclear reactions is the main tool to calculate cross sections at low energies for middle- and high- mass nuclei. Despite the fact that the underlying physics is simple and well understood, the accuracy of such calculations does not reach the predictive power required for many astrophysical problems. Uncertainties can reach the factor of two for nuclei close to the stability line and even higher for radioactive nuclei.

The accuracy of HF theory is determined by the accuracy of its input parameters, namely the optical potential parameters, level densities and γ–strength functions. A very active program at the Edwards Accelerator Laboratory of Ohio University is pursuing research to determine these input parameters, using systematic studies of particle evaporation spectra obtained from experiments with deuteron, ^{3}He, and ^{6,7}Li projectiles. The objective is to establish reliable information on the behavior of the HF input parameters for nuclei off stability and deformed nuclei. Another objective of the research is an independent determination of the γ–strength functions, which are studied in collaboration with the Cyclotron Laboratory of Oslo University. One important recent finding is that the γ-strength function experiences a considerable enhancement in the low energy region (E_γ < 3 MeV) for nuclei in the mass range 50-60 and around 90. This is in contradiction with current theoretical models and has a very large impact on (n, γ) cross sections off the stability line.

Although these parameters have been determined experimentally for some stable nuclei, they are completely unknown for nuclei off of the line of stability. This motivates studies with radioactive beams from the next generation of nuclear physics facilities (NSCL/FRIB/Atlas etc…). Development of such an experimental program will also provide the necessary experimental ground for refining nuclear reaction codes such as EMPIRE and TALYS used for the evaluations of nuclear reaction data for the

U.S. nuclear data program and for the prediction of astrophysical cross sections.

Results from this program were published in
A. V. Voinov, S. M. Grimes, C. R. Brune, M. J. Hornish, T. N. Massey, and A. Salas, Phys. Rev. C76, 044602 (2007).
S. M. Grimes, Phys. Rev. C88, 024613 (2013).
A. Voinov, S. M. Grimes, C. R. Brune, M. Guttormsen, A. C. Larsen, T. N. Massey, A. Schiller, and S. Siem, Phys. Rev. C81, 024319 (2010).
A. Voinov, E. Algin, U. Agvaanluvsan, T.Belgya, R. Chankova, M. Guttormsen, G. Mitchell, J.Rekstad, A. Schiller, and S. Siem, Phys. Rev. Lett. 93, 142504 (2004).

A research program which is actively pursued at the Nuclear Structure Laboratory of Notre Dame concerns the effects and implications on cross section calculations arising from HF input models. Recent r-process simulations, performed using rates obtained from the TALYS and NON-SMOKER codes, have indicted that model dependent features, such as those originating from nuclear input parameters in Hauser-Feshbach calculations, can propagate through to abundance predictions. These model differences stem from two primary sources, including code-dependent numerical effects, and input parameter implementation details. An active effort at Notre Dame has been focused on examining these two aspects. This has involved developing two new HF codes, CIGAR (Capture Induced GAmma-ray Reactions) and SAPPHIRE (Statistical Analysis for Particle and Photon capture and decay of HIgh energy REsonances). The codes have been developed to contain an overlapping set of identically implemented nuclear model input parameters, allowing the effects of numerical approximations and truncation on HF calculations to be directly investigated.

The investigation of cutting edge input models on HF cross section calculations is also a very active research area at the NSL. The objective is to refine HF cross sections with the latest available data and models in order to produce high quality calculations for other applications. Current theoretical efforts are centered on three main aspects. The first is the origin and modeling of the low energy γ-strength function enhancement, indicated by shell-model calculations to be M1 in nature, which has been observed for some nuclei. An ongoing effort is focused on including a new M1 γ-strength function model into HF calculations. The second aspect is investigating the effects of a new, state-of-the-art spin and parity-dependent shell-model level-density treatment for HF calculations. The third area of research being actively pursued at the NSL is the inclusion and investigation of a new global α-particle optical-model potential on HF calculations.

Results from the HF research program have been published in M. Beard, E. Uberseder, R. Crowter and M. Wiescher, Phys. Rev. C 90, 034619 (2014).

3.10 Nuclear Equation of State

Studies of the Nuclear Compressibility through Measurement of the Breathing Mode State : *At Texas A&M University*
The compressibility of nuclear matter (K_{NM}) and the asymmetry behavior (K_{SYM}) is studied through measurements of the breathing mode, Giant Monopole Resonance (GMR) state. In the last five years, an experimental program at the Texas A&M cyclotron laboratory has shown (1) that the results for ^{24}Mg and ^{28}Si agree with a K_{NM} from heavier nuclei ($K_{NM} \approx 230$ MeV) but (2) the position of the breathing mode state in some nuclei (particularly in ^{92}Zr and ^{92}Mo but also in Ca and Ni isotopes) is NOT explained by mean field calculations (Figure 10), suggesting a significant nuclear structure effect. This effect might alter the presently accepted K_{NM} extracted from breathing mode energies using mean field calculations. Understanding the nuclear structure effects will provide a better basis for K_{NM} and K_{SYM}.

With the ongoing progress of the T-Rex laboratory upgrade for re-accelerated exotic ion beams, similar experiments will be performed on exotic nuclei at Texas A&M, with the goal to study the systematic dependence on the neutron-proton asymmetry. The experiments will be performed with new light-particle detectors covering the full solid angle in coincidence with the residual heavy nucleus, to be measured in the Multipole-Dipole-Multipole Spectrometer.

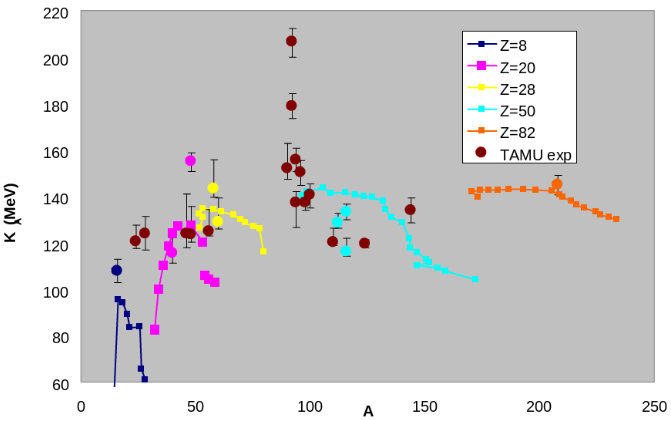


Figure 10: Squares: HFB-QRPA: Sly4 with pairing, K_{NM}=252 MeV, K_τ=-500 MeV, P. Veselý et al. PRC 86, 024303(2012). Circles: K_A from TAMU GMR data. Colors correspond to particular isotopes as shown, while for the color brown no corresponding calculations are given.

First Observation of the Asymmetry Dependence of the Caloric Curve :
At Texas A&M University
The nuclear equation of state (EOS) is of fundamental importance in describing properties of nucleonic systems, and as such is a recurring theme in the Long Range Plan (LRP). The EOS, which describes the relationship between the thermodynamic parameters and the bulk nuclear properties, is relevant in heavy ion collisions and environments of nucleosynthesis. The nuclear EOS is well characterized near beta-stability, so the neutron-proton asymmetry is increasingly studied in relation to the EOS. The lack of understanding in how the asymmetry impacts the caloric curve represented an opportunity to make a leap forward in understanding the nuclear equation of state.

We have studied the decay of isotopically reconstructed quasi-projectiles (QPs) produced in heavy ion collisions at 35 MeV/u. The excitation energy is determined from charged particle kinetic energies, neutron multiplicities, and the Q-value of the QP breakup. The neutron-proton asymmetry of the QP is calculated directly from the charged particles and neutrons attributed to the decay of the QP. The temperature of the QP is calculated using several charged particles as probes and multiple methods of temperature determination.

Figure 11 shows the ≈1 MeV decrease in temperature with increasing asymmetry. For all probes, the temperature rises with increasing excitation energy as expected and decreases significantly with increasing asymmetry. The strength of this measurement lies in the knowledge of the composition of the excited system (via isotopic reconstruction of the QP), which allows this measurement to succeed where others had failed. In this way, we have measured for the first time a clear asymmetry dependence of the nuclear caloric curve, which represents a leap forward toward understanding the nuclear equation of state.

Confirmation of this seminal observation ought to probe the caloric curve in an independent manner, avoiding the necessity of a free neutron measurement. For these measurements, the system composition must be fully constrained by the entrance channel and the reaction mechanism. By measuring the evaporation residue and evaporated particles without reliance on free neutrons, the temperature may be extracted with minimal systematic uncertainty. Moreover, the density and pressure will be extracted to gain a larger perspective of the asymmetry dependence of the relations between the thermodynamic parameters.

The recently commissioned QTS Spectrometer at the Texas A&M University Cyclotron Institute is ideally suited to measuring the heavy residues with good efficiency and resolution. The focusing spectrometer may be used in conjunction with the charged-particle detector FAUST to measure the evaporated particles with good energy resolution and position resolution. Such a detector suite is well poised to take advantage of heavy rare-isotope beams when they become available.

Effects of Clusterization on the Low-Density Equation-of-State :
At Texas A&M University
Conventional theoretical calculations of nuclear matter properties based on mean-field approaches fail to give the correct low-temperature, low-density limit, which is governed by correlations, in particular by the appearance of bound states. New data from heavy-ion collisions have been used to probe clusterization at temperatures and densities compa-

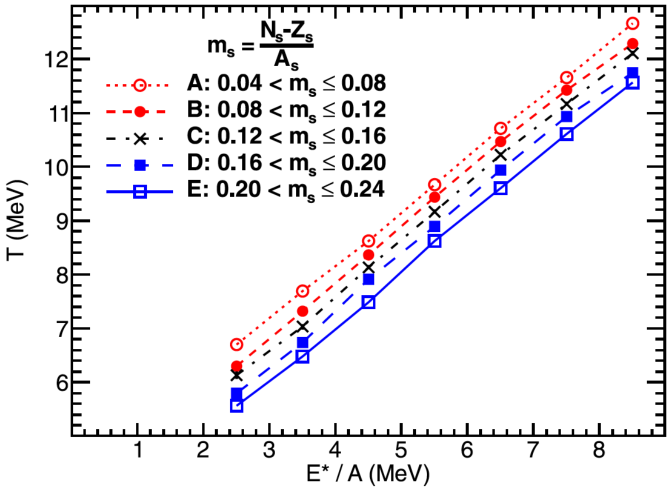


Figure 11: Caloric curves for isotopically reconstructed sources extracted with the momentum quadrupole fluctuation method using protons as the probe particle. Each curve corresponds to a narrow range in source asymmetry (ms).

rable to those expected for the neutrinosphere in a supernova explosion. These data are being used to test astrophysical equations of state at low density. From the data, in-medium cluster binding energies for d, t, ^{3}He, and α-clusters, produced in low density nuclear matter and the free symmetry energy and the internal symmetry energy at sub-saturation densities and temperatures are extracted. The symmetry energy of nuclear matter is a fundamental ingredient in the investigation of exotic nuclei, heavy-ion collisions, and astrophysical phenomena. A recently developed quantum statistical (QS) approach that takes the formation of clusters into account predicts symmetry energies that are in very good agreement with the experimental data. Proper treatment of in-medium effects in astrophysical equations of state should improve the utility of those for modeling astrophysically interesting events.

K. Hagel, J.B. Natowitz and G. Roepke, *The equation of state and symmetry energy of low-density nuclear matter* European Physical Journal A 50 39-1 - 39-16 (2014) *and references therein.*

3.11 Prospects for Discovering New Super-Heavy Elements

At Texas A&M University

In the last 15 years, several super-heavy elements have been discovered using a single, exceptional projectile: ^{48}Ca. These discoveries used nuclear reactions where two nuclei fuse together to form a "compound nucleus" containing all of the protons and neutrons originally in the two reacting nuclei. ^{48}Ca has an unusually high neutron-to-proton ratio, and this impacts its ability to form super-heavy elements. Unfortunately, all possible reactions which could potentially produce new elements using ^{48}Ca have already been studied, so a new projectile will be needed. Experiments at Texas A&M University have been evaluating whether ^{45}Sc and ^{50}Ti could be used as projectiles to produce new super-heavy elements. The data suggest that these projectiles create compound nuclei which are more likely to fission (to split back into two nuclei) rather than stay fused. As a result, forming new super-heavy elements will likely be extremely difficult, possibly requiring upgrades to existing facilities.

D. A. Mayorov, T. A. Werke, M. C. Alfonso, M. E. Bennett, and C. M. Folden, III *Production cross sections of elements near the N=126 shell in Ca48-induced reactions with Gd154,Tb159,Dy162, and Ho165 targets* Phys. Rev. C 90, 024602 (2014)

3.12 Surrogate Reactions for n-Induced Fission

Texas A&M University, with a group from the University of Richmond

The Richmond group carries out an active program on surrogate reactions for neutron-induced fission and inelastic neutron scattering on actinide targets, performed with the STARLITER array at Texas A&M University. The surrogate reaction program aims to test the efficacy of the surrogate reaction technique to extract (n,f) and (n,xnγ) cross sections for unstable nuclei. Direct measurements of such cross sections are difficult or impossible for short-lived species. The surrogate reaction produces the same compound system as the direct neutron-induced reaction but exploiting a stable beam and target combination. A measurement of the decay probabilities and a calculation of the formation probability yields the cross section of interest, assuming the system is equilibrated and that the spin/parity/excitation energy distributions are similar.

The primary apparatus for these investigations at Texas A&M University is the STARLITER array. STARLITER, developed and commissioned by a group at LLNL, consists of a highly segmented Si detector array (STARs, the Silicon Telescope Array for Reaction studies) to detect light charged-particle and fission fragments coupled to the 5-6 Compton-suppressed Ge detectors of the LITER (LIvermore TExas Richmond) array. Typical detection efficiencies are 20% for light charged particles, 30% for fission fragments and 5% (200 keV) and 1.5% (1.3 MeV) for γ rays.

The results for (n,f) cross sections show remarkable agreement with the evaluated databases: agreement is typically within 5-10% of the accepted values for multiple different reactions and nuclei. The latest results, $^{236}\mathrm{Pu},^{237}\mathrm{Pu}$ and $^{238}\mathrm{Pu(n,f)}$ measurements based on a recent experiment at the Texas A&M Cyclotron Laboratory, have been published. The results for $^{237,238}\mathrm{Pu(n,f)}$ show good agreement with the database values. However, the surrogate cross section for $^{236}\mathrm{Pu(n,f)}$ deviates significantly, in both magnitude and trend, from the ENDF values. It is of note that in this case there are essentially no data to guide the database (model) values.

R.O. Hughes, C.W. Beausang, T.J. Ross, J.T. Burke, R.J. Casperson, N. Cooper, J.E. Escher, K. Gell, E. Good, P. Humby, M. McCleskey, A. Saastimoinen, T.D. Tarlow, and I.J. Thompson, *Pu^{236}(n,f), Pu^{237}(n,f), and Pu^{238}(n,f) cross sections deduced from (p,t), (p,d), and (p,p) surrogate reactions*, Phys. Rev. C 90, 014304 (2014).

4 The Scientific Impact of ARUNA: Fundamental Symmetry Studies

Many groups working on studies of fundamental interactions or searches for physics beyond the Standard Model have found the ideal environment, complementary to that of the national laboratories and large nuclear physics facilities, at some of the ARUNA labs. These experiments usually need extended experimental studies to understand and minimize systematic uncertainties, which can take long periods of on-line beam time. Thus, in many cases it is difficult to run these experiments at large facilities where beam time is limited and setups need to be disassembled to yield space for other experiments.

4.1 Testing CVC and CKM Unitarity via Superallowed $0^+ \rightarrow 0^+$ Nuclear Beta Decay

At Texas A&M University

Conservation of the vector current (CVC) and the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix are fundamental pillars on which the Standard Model was built. Tests of their validity make it possible to exclude potential scenarios for new physics. For several decades, measurements on superallowed $0^+ \rightarrow 0^+$ nuclear β transitions have tested CVC and been the source of the most precise value for V_{ud}, which in turn has yielded the most demanding test of CKM unitarity. The uncertainties on all these results have been substantially and continuously reduced over that period of time. In addition, the observed constancy of the effective coupling with respect to the β-decay Q values for the superallowed transitions has been used to put the most sensitive limits so far on possible Scalar contributions to weak decays.

During the last 5 years, the group of John Hardy and collaborators (Texas A&M) have measured precise half-lives ($\pm$0.03%) for the superallowed emitters ^{26}Si, ^{26}Al^m, ^{30}S, ^{38}K^m, ^{38}Ca and ^{46}V, Q_{EC} values ($\pm$80 eV) for the superallowed emitters ^{10}C, ^{34}Ar, ^{38}Ca and ^{46}V and branching ratios ($\pm$0.1%) for the superallowed transitions from ^{34}Ar and ^{38}Ca. In all cases, the precision they have achieved is unsurpassed by any other group worldwide and, in most cases, it is also unmatched by any other group. As a long-term goal, they plan to complete all four accessible mirror pairs, $^{26}\mathrm{Si} \rightarrow {}^{26}\mathrm{Al}^m \rightarrow {}^{26}\mathrm{Mg}$, $^{34}\mathrm{Ar} \rightarrow {}^{34}\mathrm{Cl} \rightarrow {}^{34}\mathrm{S}$, $^{38}\mathrm{Ca} \rightarrow {}^{38}\mathrm{K}^m \rightarrow {}^{38}\mathrm{Ar}$ and $^{42}\mathrm{Ti} \rightarrow {}^{42}\mathrm{Sc} \rightarrow {}^{42}\mathrm{Ca}$. Depending on the results, these cases could constrain the calculated isospin-symmetry-breaking corrections enough to reduce

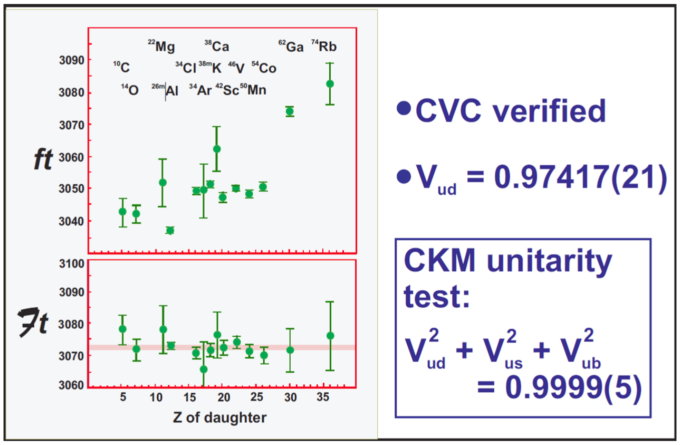


Figure 12: The extraction of V_{ud} and the verification of the conservation of the vector current have been constrained using data from ARUNA labs. The top left shows the measured ft values. When corrected for isospin-symmetry breaking and radiative effects, the $\mathcal{F}t$ values show independence of Z. This is used to put limits on the violation of CVC and gives confidence in the isospin-breaking corrections. (Courtesy: John Hardy).

the systematic uncertainty on V_{ud}, and thus improve the unitarity sum.

New test of Isospin Symmetry Breaking

At Texas A&M University

A new and powerful test of isospin-symmetry-breaking effects in nuclear beta decay has been demonstrated at the Texas A&M Cyclotron Institute by a precise measurement on the decay of ^{38}Ca, a nucleus with a half-life of only 444 ms. One mode of decay for ^{38}Ca is a so-called "superallowed" branch, which exclusively occurs via the vector weak interaction. By determining the fraction of ^{38}Ca decays that follow this path, the experimenters established the overall strength of the transition, referred to as its ft value, with $\pm 0.2\%$ precision. They then compared that result with the ft value for a similar transition in the decay of ^{38m}K. These two transitions are described as mirrors of one another because the nuclear structure of their initial and final states is very similar and, indeed, would be identical if the neutron and proton were identical particles. It turns out that the small difference between the ft values for such a pair of transitions is a sensitive measure of the effects of the proton-neutron differences themselves, i.e., isospin symmetry breaking. This result, once combined with planned future comparisons of mirror superallowed transitions, is expected to result in an improved test of the unitarity of the CKM matrix. This has deep implications since any experimentally observed deviation from unitarity would signal the existence of new physics beyond the Standard Model.

Figure 13: Dan Melconian and students near the TAMUTRAP setup.

H.I. Park, J.C. Hardy, V.E. Iacob, M. Bencomo, L. Chen, V Horvat, N. Nica, B.T. Roeder, E. Simmons, R.E. Tribble, and I.S. Towner, *β Decay of Ca^{38}: Sensitive test of Isospin Symmetry-Breaking Corrections from Mirror Superallowed $0^+ \rightarrow 0^+$ Transitions*, Physical Review Letters 112, 102502 (2014).

Addional Techniques for the study of superallowed β–decays

At Texas A&M University

The group of Dan Melconian and collaborators (also at Texas A&M) is setting up an ion trap (TAMUTRAP) to do precision determination of beta-delayed proton decays of the $A = 4n$ $T = 2$ nuclei and test isospin symmetry breaking corrections which affect the extraction of V_{ud}.

Lynn Knutson (Madison, Wisconsin), Elizabeth George and Paul Voytas (Wittenberg University) and collaborators have set up an iron-free spectrometer and performed precise determinations of the shape of beta spectra. They have published work from ^{66}Ga and are presently working on the determination of the ^{14}O spectrum, which could potentially affect the extraction of V_{ud}.

4.2 Precision Determination of Correlations in Nuclear Beta Decays to Search for Scalar and Tensor Currents

At University of Washington, with groups from Argonne National Laboratory, etc. At Texas A&M University. At Lawrence Berkeley National Laboratory (Not an ARUNA member)

Conservation of angular momentum combined with the left-handedness of the weak interaction yield clear prescriptions for angular correlations involving the electron and neutrino. Scalar and tensor currents, with chiralities opposite those of the Standard Model, would produce effects on these correlations and on the shape of the spectra which allow for sensitive searches in particular nuclei. Several groups are working at ARUNA labs using novel techniques for improving sensitivity.

Figure 14: Graduate students David Zumwalt and Yelena Bagdasarova at work at the laser setup at the University of Washington, Seattle. David Zumwalt contributed to developing a source for producing ^{6}He which currently is the most intense in the world.

In order to determine the correlations it is necessary to detect the slow recoiling nuclei, so it helps to use ion or atom traps to have minimal interference on the decaying particles.

Yuan Mei, Brian Fujikawa, and collaborators at Lawrence Berkeley National Laboratories are working on an electrostatic ion beam trap (EIBT) that should allow them trapping of ^{19}Ne and ^{6}He and determination of the electron-antineutrino correlation.

The group of Dan Melconian and collaborators (at Texas A&M) is setting up the largest open Penning ion trap (TAMUTRAP mentioned in the previous section) to do precision determination of correlations in beta-delayed proton decays of $A = 4n$ $T = 2$ nuclei.

A collaboration (P. Müller, A. Garcia, spokepersons) between Argonne National Laboratory, University of Washington (Seattle), LPC (CAEN, France), and Michigan State University is working on the determination of the electron-antineutrino correlation from ^{6}He.

All these experiments are presently working towards determinations of the correlations at the subpercent level, aiming for a goal of $\sim 0.1\%$, competing worldwide with the most sensitive experiments.

5 The Scientific Impact of ARUNA: Applications of Nuclear and Radiation Methods to Other Fields of Science

The majority of the ARUNA laboratories support "applied" programs, meaning the use of accelerator facilities and methods of particle and radiation detection for other areas of science. These programs are natural for the unversity-based ARUNA laboratories, since a wide variety of scientific and engineering expertise is concentrated on university campuses. ARUNA facilities provide opportunities for cross fertilization of ideas and suggestions and are ideally situated for applications in the nuclear and radiation sciences.

The applied programs also play an important role in the educational mission of ARUNA laboratories, which will be described in more detail in Section 6. The campus presence of ARUNA facilities, together with the opportunity to participate in applied science, is attractive to students. As natural hosts to inter-disciplinary research programs, ARUNA laboratories are the first point of contact with the nuclear science field for many undergraduate students. The importance of applied programs for the science education of undergraduate students is exemplified in the two undegraduate institutions, Hope College and Union College, who are members of ARUNA.

5.1 Ion Beam Analysis:

At Hope College, Union College, University of Notre Dame, TUNL, Florida State University

The α-scattering experiment that Rutherford interpreted to establish the existence of the nucleus, founding our field, is used in the ARUNA laboratories, as it is around the world, to characterize materials. In addition to Rutherford backscattering (RBS), proton-induced X-ray emission (PIXE), proton-induced gamma-ray emission (PIGE), and other techniques are used in our laboratories as research and teaching tools. These relatively simple methods allow for projects that are well adapted to undergraduate research. At the Hope College Ion Beam Analysis Laboratory, a research program takes undergraduate students from the analysis of trace elements in glasses for art and archeology studies to characterization of metalloproteins. Systematic studies of consumer products also have been performed to evaluate the usage of flame-retardent chemicals in car seats or perfluorinated compounds in cosmetics and food containers. In addition to exciting scientific results and a significant number of publications, the undergraduate students are learning the key elements of the scientific method.

At the University of Notre Dame, an applied program in art analysis has been developed in collaboration with the Department of Anthropology, and involves undergraduate students from that Department. Through this program, which is supported by the University, pottery samples from the US Southwest Anasazi sites have been analyzed using PIXE techniques, see Fig.15. Of particular interest was the pigment composition of the painted pottery surface. Through the organization of this program and the development of a special multidisciplinary seminar, strong communication links have been established with the non natural science academic community at Notre Dame.

This program has now expanded into a collaboration with the rare book collection of the Notre Dame libraries to study and identify medieval book painting techniques and monastery artists and painting schools.

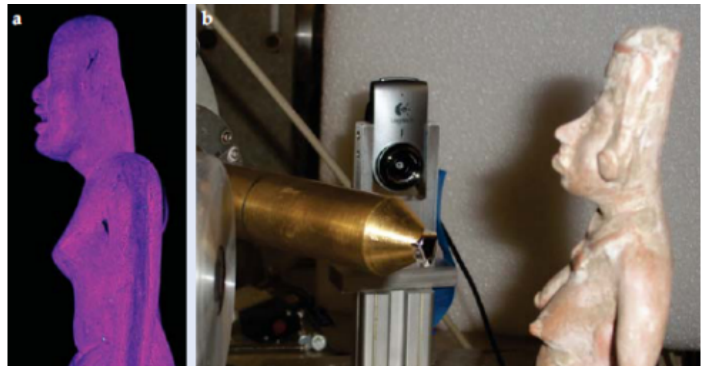


Figure 15: (a) Exposing an artifact to UV light reveals the location of pigments invisible to the unassisted eye (b) Proton-induced x-ray emission (PIXE) provides quantitative details of the pigment composition; in particular, it reveals the iron and manganese content of the paint.

At the Triangle Universities Nuclear Laboratory, characterization of membranes for water purification by RBS and elastic recoil detection (ERD) analyses have been performed, and a publication with an undergraduate student as first author has been submitted.

At the Triangle Universities Nuclear Laboratory, a multidisciplinary study of the impact of increased CO_2 concentrations in the atmosphere due to human activities is being performed. ^{11}C is produced at the TUNL Tandem laboratory, $^{11}CO_2$ is then injected into growth chambers for corn plants. An innovative method, called PhytoPET developed at Jefferson Laboratory, is being used to dynamically follow the path taken by the ^{11}C in the plants.

At Hope College, a method is being developed for isotope harvesting of ^{67}Cu from the beam stop of the Facility for Rare Isotope Beams (FRIB). This isotope can be used for positron emission tomography but more importantly, it is used to target specific cancerous tumors while imaging them at the same time using the single-photon emission computed tomography (SPECT).

At the University of Notre Dame, a program to systematically study the $\mathrm{Mo(p,Xn)^mTc}$ is underway to evaluate the dosimetric contamination that may occur in the accelerator-based production of $^{99}\mathrm{Tc}^m$. This isotope is used in 90% of nuclear medicine procedures in the US. There is currently a risk of shortage as the standard method of production, which uses highly enriched Uranium, is being phased out.

An accelerator mass spectrometry (AMS) program has been developed at the University of Notre Dame. While standard ^{14}C AMS techniques are primarily used for undergraduate student training, new AMS probes from ^{44}Ti to ^{60}Fe have been developed for geological, hydrological, and meteorological applications.

5.2 Homeland Security and National Nuclear Security

Much of the equipment used by border control agent originates from developments in nuclear science. ARUNA laboratories are investigating new methods for security.

At the Triangle Universities Nuclear Laboratory, studies are performed to provide crucial data to a non-intrusive active interrogation system using nuclear resonance fluorescence (NRF). The objective of the measurement is to demonstrate that key elements (^{240}Pu, ^{237}Np, ^{233}U) have states that can be excited by the proposed source. The source produce gamma rays between 2 and 4 MeV. In addition, TUNL is studying photo-fission induced by polarized γ rays as a new material analysis method.

5.3 Neutron Physics and Inertial Confinement Fusion (ICF)

At Ohio University, with a group from SUNY Geneseo and University of Notre Dame

At the Ohio University Edwards Accelerator Laboratory, a unique national facility for neutron science, the applied program is centered around the 4.5-MV tandem accelerator designed to support high beam intensities. The majority of the applied nuclear physics work at this laboratory involves neutron production and/or detection. The combination of continuous and mono-energetic neutrons together with a well-shielded 30-meter fight path does not exist anywhere else in North America. This combination of equipment permits measurements with high resolution and low background.

Two ongoing projects in the lab are the study of fast neutron transmission in iron. Other projects, which are led by outside users, include neutron imaging, neutron detector calibration, studies of neutron damage of electronics, and a measurement of the $^{12}\mathrm{C(n,2n)}^{11}\mathrm{C}$ cross section. The latter project is part of an effort to develop a high-energy neutron diagnostic for inertial confinement fusion (CF) facilities, led by external users involving a dozen undergraduate students from the State University of New York in Geneseo, NY. In the same context, the measurement of the ^{3}H(d,γ) and ^{3}H(d, n) branching ratio important for understanding ICF diagnostics is underway.

5.4 Radiation chemistry

At University of Notre Dame

The radiation chemistry program at the University of Notre Dame Nuclear Science Laboratory focuses on the fundamental physical and chemical processes involved in the passage of ionizing radiation through matter. Although the research examines basic processes involved in radiolysis, the information is directly applicable to a wide variety of scenarios in the fields of medicine, engineering, and environmental studies. Specific progress made in the nuclear power industry includes addressing problems in reactor water chemistry, waste storage and fuel reprocessing. The goal of these particular studies is to derive fundamental information on radiation effects to allow for the safe and economical development and management of nuclear power. Secure storage of radioactive waste is one of the main elements of this program to ensure a pristine environment and public safety. Other applications related to medical therapy, space exploration, and homeland security are being explored.

The group at the University of Notre Dame is in the process to develop new nuclear probes for mapping the temperature density conditions for the NIF shot environment using the $^{10}\mathrm{B}(\mathrm{p},\alpha)^7\mathrm{Be}$ reaction. Simulations have shown that reaction rate is sufficient to produce observable quantities of ^{7}Be at

NIF. First tests are being in preparation. If successful the program will be expanded to the study of plasma effects on nuclear reaction rates that are presently only estimated.

5.5 Detector development

At University of Massachusetts Lowell, University of Kentucky

The combination of a research reactor next to a 5.5-MV Van de Graaf accelerator allows for the design and a construction of the next generation neutron detectors and high-granularity germanium γ-ray detectors. The characterization of neutron detectors based on the Cs_2LiYCl_6 ("CLYC") scintillator is being performed in experiments at the UMass Lowell research reactor and the University of Kentucky accelerator laboratory. The development of planar, pixellated high-purity germanium detectors is performed at the UMass Lowell accelerator. Both projects are leveraged with private industry through SBIR-grants.

6 Education and Workforce Development

The ARUNA facilities play an important role in the research and education missions of the field of nuclear science. The important contributions to research have been outlined already. In this section, we concentrate on the contributions in terms of education and outreach. The research programs at the ARUNA facilities are conducted in an environment that is optimized for graduate education in experimental nuclear science, mentoring young scientists and providing research opportunities for undergraduate students.

Faculty at ARUNA facilities are dedicated to maintaining an environment that engages students in all aspects of research from concept development, experimental preparation and execution, through data interpretation to the dissemination of results. The small-group environments at these facilities provides opportunities for graduate students and undergraduates to work closely with postdocs and faculty, to have hands-on research experiences, and ultimately to provide leadership on thesis projects. The on-campus presence of the ARUNA laboratories is an important factor in attracting the brightest students to the field of nuclear science.

The location of these facilities at universities makes the educational reach very broad, impacting the undergraduate students, graduate students, postdocs, faculty and administrators within the university, as well as the general public in the communities in which the universities exist.

The report on the implementation of the 2007 Long-Range Plan [1] lists the number of Ph.D. graduates, distinguished by research area, year and institution. This report shows that, during the period of 2006-2012, close to 40% of the Ph.D's in low-energy nuclear science and nuclear astrophysics were granted by the institutions of the ARUNA laboratories (including the Yale University group). The majority of those Ph.D. dissertations include experiments from ARUNA laboratories, where many projects were connecting local experiments with experiments at national user facilities. A table of the ARUNA Ph.D. graduates 2006-2015 is given at the end of this section. The seven largest ARUNA facilities (FSU, Kentucky, Notre Dame, Ohio, TUNL, TAMU, UMass) currently host 75 undergraduate researchers and 37 postdocs.

6.1 Undergraduate Students get Involved

Undergraduate students are the lifeblood of a university and of an ARUNA laboratory. The research groups at ARUNA facilities routinely involve undergraduate students in their work as undergraduate research assistants (URA). The URA positions are usually funded by research grants of the groups or by the universities, and many undergraduate students work on research projects throughout the year.

Additionally, a number of the ARUNA laboratories have research experience for undergraduates (REU) programs in the summer or connections with predominantly undergraduate institutions that bring students for the summer for research experiences. For example, Texas A&M has had a nuclear science REU program for over 10 years, exposing over 120 students to nuclear science, predominately from schools where they would have limited or no exposure to nuclear science in their undergraduate curriculum. The ND REU program, funded for more than 25 years, involves an average of 5-10 students in the nuclear lab. At TUNL an NSF-funded REU program involves 8 students in a 10-week research experience.

In many cases the connections to these undergraduate institutions are scientists, who came through the ARUNA laboratories. One example of the role ARUNA labs play beyond their own students is the 30 undergraduate students from the University of Dallas that Prof. Sally Hicks has brought to the University of Kentucky Accelerator Laboratory (UKAL) to engage in research over the past 20+ years. Professor Sally Hicks herself came through UKAL and now shares her knowledge of and excitement for nuclear physics with students that otherwise would likely have no exposure to this field of science. Of the undergraduate students who participated, 42% received a physics or engineering Ph.D.

Professor Shelly Lesher is beginning a similar tradition of bringing undergraduate students from the

University of Wisconsin at La Crosse with her to the University of Notre Dame and the UKAL for summer research experiences. These students are not only learning nuclear physics, but they are gaining valuable skills.

Benefits of undergraduate research experience:

- Technical skills
- Creative problem solving skills
- Scientific communication skills
- Dealing with frustrations / perseverance
- Self-confidence
- Time management
- Project planning
- Working within a collaboration
- Leadership development

In addition to the students who make the commitment to do an undergraduate research project, there are other undergraduates who get exposed to nuclear physics by working at the laboratory in various capacities. At many ARUNA laboratories you can find undergraduates involved across the full spectrum of the laboratory. Some may work on construction projects, others as part of the computer group, some on the accelerator, and others are imbedded in the research groups. In the case of the applied programs, non-science undergraduate students get exposed to nuclear physics techniques. All of these are valuable contributions to education and increase the understanding and acceptance of nuclear science in a broad group of individuals.

6.2 Teaching is Impacted by the ARUNA Facilities

Faculty at ARUNA facilities teach classes at the host university. This results in many more people being exposed to nuclear science. We bring our research into the classroom and we bring the students through the facilities.

For example, the 1.1-MV Pelletron tandem accelerator at Union College is used for PIXE and RBS experiments in two physics courses and for undergraduate research projects in ion-beam analysis each year. It is also used in an annual workshop for high school students and physics teachers. In the last ten years, over 230 undergraduate students, 110 high school students, and 40 high school teachers have gained experience with the accelerator.

Additionally, there is often unique curricular development both in terms of components within a general physics or chemistry course and specialty courses that take place at universities with ARUNA facilites. At Hope College students in general chemistry might be challenged to think through the implications of food irradiation when they do the case study of a "Benign Hamburger" (ref: G. F. Peaslee, J. M. Lantz, M. M. Walczak; "The Benign Hamburger"; J. College Sci. Teaching, 28 21 (1998)). At the University of Notre Dame, many students learn about nuclear concepts in a course called Physics Methods in Art & Archaeology. (Ref `http://isnap.nd.edu/Lectures/phys10262_2011/`) Imbedding nuclear concepts into existing courses and developing specialized courses are ways to improve students' science and nuclear science literacy.

6.3 Graduate Students are Pushing the Frontiers of Science

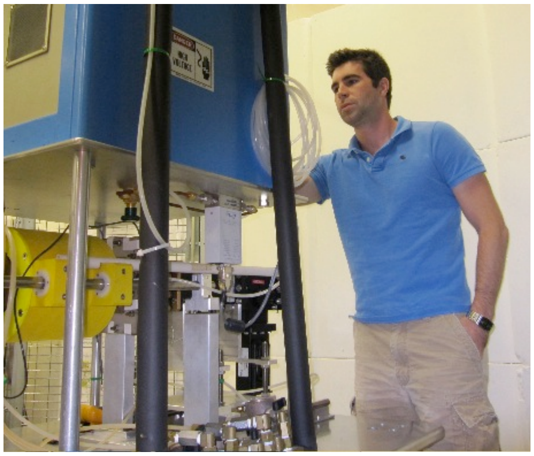
Graduate students are the future of the field and the feedstock for the workforce needed by the national laboratories. Graduate students at ARUNA laboratories get an unparalleled educational experience, learning everything from tuning accelerator beams through cutting edge nuclear physics. They learn everything from conceiving and planning an experiment through building of experimental equipment, in some cases repairing the accelerator and beam delivery, to analyzing data. ARUNA laboratories provide training in vacuum technology, accelerator operation, detector design, electronics, and data acquisition at a level that is not possible at larger national user facilities, where access is limited and technical staff is often responsible for setting up and aligning experiment and experimental equipment. Additionally, graduate students at ARUNA laboratories also live among the larger physics community in their departments, thus increasing the appreciation for our field in a larger community.

6.4 Examples of Recent Graduates

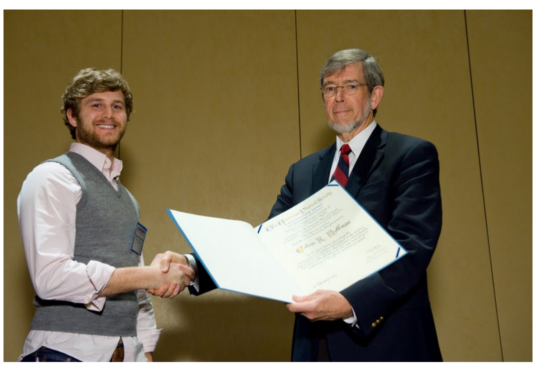
Mary Kidd is an an assistant professor at the Tennessee Technological University in 2012. Mary received a B.S. in physics in 2004 from Tennessee Technological University and a Ph.D. in physics from Duke University in 2010. Her research specialty is experimental nuclear physics. She conducted her Ph.D. dissertation research on two-neutrino double-beta decay measurements at the Kimballton Underground Research Facility under the supervision of Professor Werner Tornow. After completing her degree in 2010, she conducted research at Los Alamos National Laboratory as a postdoc in the weak-interactions group.

Daniel Sayre is currently a research staff member at Lawrence Livermore National Laboratory, working on nuclear diagnostics for the National Ignition Facility. Daniel received is B.S. in physics from Ohio University in 2005 and a Ph.D. in Physics from Ohio University in 2011. His thesis research on the fusion of ^{4}He and ^{12}C was performed with the tandem accelerator at Ohio University under the supervision of Carl Brune.

Matthew Kiser is a Senior Scientist at National Security Technologies, LLC, and is stationed at the Remote Sensing Laboratory located at Andrews Airforce Base in Maryland. Matthew received B.S. degrees in physics and mathematics from King College in 2002. He received a Ph.D. in physics from Duke University in 2008 with specialty in experimental nuclear physics. His Ph.D. dissertation project was the development of techniques to study plant physiology using tracking of short-lived radioisotopes. His thesis research was carried out in the tandem laboratory at TUNL under the supervision of Calvin Howell.



John Cesaratto is currently a Toohig Fellow in Accelerator Science at SLAC in the LHC Accelerator Research Program. John received a B.S. with major in physics from John Carroll University in 2005 and a Ph.D. in physics from the University of North Carolina at Chapel Hill in 2011. He conducted his thesis research at the LENA facility on developing beam capabilities to enable measurements of nuclear reaction rates important to understanding elemental variations in globular cluster stars. Art Champagne and Thomas Clegg supervised his dissertation research.



Calem Hoffman is an Assistant Physicist at Argonne National Laboratory. His research interests are the shell structure of exotic nuclei. Calem received a B.S. in physics from Florida State University in 2003, and a Ph.D. in Physics from Florida State University in 2009 on research performed at the NSCL, on the magic character of ^{24}O. His Ph.D. dissertation was awarded the Dissertation Award in Nuclear Physics American Physical Society Division of Nuclear Physics, February 2010. His thesis advisor was Samuel L. Tabor.

6.5 Postdocs are Junior Colleagues and Future Researchers

ARUNA laboratories educate postdocs, often treating them as junior colleagues. It is not uncommon for postdocs at ARUNA facilities to also get experience teaching to help prepare them to transition into faculty positions, should they decide on that career path.

6.6 ARUNA Facilities Provide for Widespread Visibility

Many members of the public visit the ARUNA facilities. From members of Congress who are having face time at their local university, to the undergraduate students mentioned above, to parents of students, to students from local school districts and to the general public, the ARUNA laboratories play an important role in raising the nuclear science literacy of the general public. Because these facilities are distributed throughout the country, it is much more likely that there will be an ARUNA facility, with an enthusiastic tour guide, close by for a teacher to take his/her students than a national facility.

Researchers at ARUNA facilities are active in science education in the schools and of the general public in their local areas. Through combinations of personal contacts and established institutional relationships, faculty, postdocs and graduate students create opportunities for people in the region to learn about nuclear physics and more generally about the science of the physical world. Educational outreach activities include giving presentations and demonstrations in the classrooms of local K-12 schools, providing tours of the research facilities for students and teachers in the local schools, and participating in the Nuclear Science Merit Badge program of the Boy Scouts of America. As an example, over the last four years researchers at TUNL have given tours of the accelerator laboratories to more than 200 students attending local schools and 400 undergraduate students. The High Intensity Gamma-ray Source (HIγS) and the Laboratory for Experimental Nuclear Astrophysics (LENA) are the main attractions for many of the tours. An example of a visit by a boy scout troop is given below. As part of its participation in the Nuclear Science Merit Badge program, TUNL provides boy scouts troops with science presentations, hands-on activities and tours of the research facilities that are appropriate for a wide age range (7th grade through high school students). See Figs. 16 and 17.

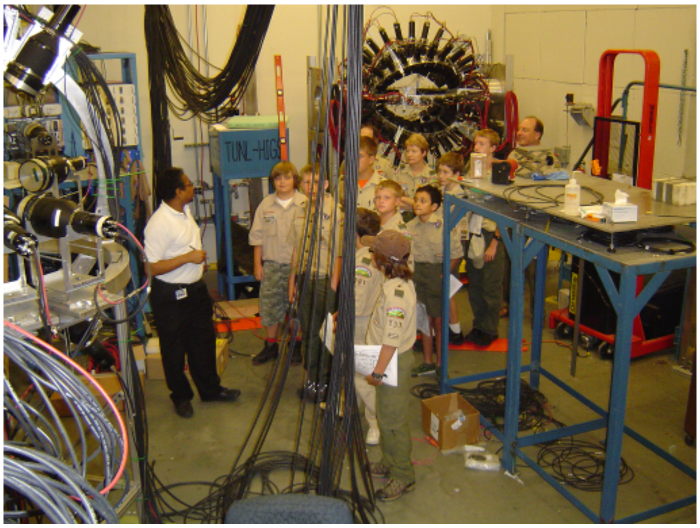


Figure 16: The scouts are exploring the large target room at HIγS.

Figure 17: The scouts in the control room of the Tandem Laboratory analyzing data.

6.7 ARUNA Experimental Ph.D. Graduates 2006-1/2015

Year	Name	Ph.D. Research Facility	Current Position (if known)
Florida State University			
2006	Pipidis, Paschalis Akis	FSU/Gammasphere (ANL)	Post Doctoral Researcher, INFN Legnaro (Italy)
2006	Roeder, Brian T.	FSU	Accelerator Physicist, Texas A&M University
2007	Diffenderfer, Eric S.	FSU	Assistant Professor of Radiation Oncology, U. of Pennsylvania
2008	Aguilar, Aaron	Gammasphere(ANL)/FSU	Staff Physicist, LLNL
2008	Cluff, Warren	FSU	Dept. of Homeland Security, Customs and Border Protection
2008	Hinners, Trisha	FSU/NSCL (MSU)	Systems Engineer at Northrop Grummnan Corporation
2008	Johnson, Eric	FSU	Deputy Director, Florida Office of Insurance Regulation
2008	Lee, Sangjin	FSU	Research Fellow at Indiana University, Institute for Basic Science
2009	Hoffman, Calem R	NSCL (MSU)	Assistant Physicist at Argonne National Laboratory, Physics Division
2009	Peplowski, Patrick	FSU	Staff Scientist at Johns Hopkins U., Applied Physics Laboratory
2009	Teal, Charles	FSU/Gammasphere(ANL)	Officer, Nuclear Regulatory Commission
2010	Reynolds, Robert R., Jr	NSCL (MSU)	
2011	Bender, Peter C.	FSU/Gammasphere(ANL)	Postdoctoral Researcher at TRIUMF, Vancouver (Canada)
2011	Rojas, Alexander	FSU	Postdoctoral Researcher at TRIUMF, Vancouver (Canada)
2012	Mitchell, Joseph	FSU	Postdoctoral Researcher at Cero Observatory
2014	Santiago-Gonzalez, Daniel	NSCL (MSU)/FSU	Postdoctoral Researcher, Louisiana State University
2014	Avila-Coronado, Melina	FSU	Postdoctoral Researcher, Argonne Natl. Lab.
2014	Kuchera, Anthony	FSU	Postdoctoral Researcher, NSCL, Michigan State University, NSCL
Ohio University			
2006	Matel, Catalin	Ohio U/TRIUMF	Staff Scientist, ELI-NP (Romania)
2008	Shukla, Shaleen	Ohio U	Physics Instructor, UNC Greensboro
2009	Oginni, Babatunde M	Ohio U	Research Scientist at Canberra Industries (CT)
2009	Adekola, Aderemi	HRIBF(ORNL)	Research Scientist at Canberra Industries (CT)
2011	Sayre, Daniel	Ohio U	Staff, Lawrence Livermore National Laboratory
2013	Cooper, Kevin	Ohio U	Assistant Professor, Lincoln Memorial University
2013	Byun, Youngshin	Ohio U/Oslo C	High School Teacher in South Korea
2014	Divaratne, Dilupama	NSCL(MSU)	Physics Instructor, Miami (OH)
2014	Ramirez, Anthony Paul	Ohio U	U. of Kentucky, Postdoc
Texas A&M University			
2006	Pochivalov, Oleksiy Grigorievich	TAMU	Oil Company in Houston, TX
2007	Al-Abdullah, Tariq	TAMU	Assistant Professor of Physics, Hashemite University of Jordan
2007	Fu, Changbo	TAMU	Distinguished Research Fellow, Dept. of Physics & Astronomy, Shanghai Tia Tong U.
2007	Keksis, August Lawrence	TAMU	Scientist at Los Alamos National Lab
2007	Peng, Yong	TAMU	Medical Physics
2007	Vuong, Au Kim	TAMU	Oil Company in Houston, TX
2007	Zhai, Yongjun	TAMU	Asst. Professor at Cooper Medical School of Rowan University, USA
2008	Chen, Xinfeng	TAMU	Medical Physics
2008	Qin, Lijun	TAMU	Hewlett- Packard Co., Houston, TX
2009	Wuenschel, Sara Katherine	TAMU	Post-Doc. at Texas A&M University
2010	Zhao, Xingbo	TAMU	Post-Doc. Dept. of Physics at Iowa State University
2010	Kohley, Zachary Wayne	TAMU	Faculty at MSU
2010	Sarah, Soisson	TAMU	Scientist at Sandia National Lab
2011	McCleskey, Matthew Edgar	TAMU	Nuclear Scientist at Baker Hughes
2011	Park, Hyo-In	TAMU	Post-Doc at Texas A&M University
2012	Goodwin, John	TAMU	Faculty at Blinn College
TUNL Duke University			
2006	Sabourov, Amanda	TUNL-Tandem	Health Physicist, SLAC
2007	Blackston, Matthew	TUNL-HIGS	Scientist, ORNL
2008	Hutcheson, Anthony	TUNL-Tandem	Staff Scientist, Naval Research Lab, Washington, DC
2008	Kiser, Matthew	TUNL-Tandem	Germanium Detector Physicist, PHDs Co.
2009	Sun, Changchun	TUNL-HIGS	Postdoc, LBL
2010	Henshaw, Seth	TUNL-HIGS	National Security Technologies, LLC
2010	Kidd, Mary	TUNL-KURF	Physics Dept., Tenn. Tech Univ.
2010	Perdue, Brent	TUNL-HIGS	Postdoc, LANL
2010	Zong, Xing	TUNL-HIGS	Trivest Advisors, Shanghai, China
2011	Jia, Botao	TUNL-HIGS	Financial Advisor, BLACKROCK
2012	Broussard, Leah	KVI(Groningen)	Postdoc, LANL
2012	Esterline, James	TUNL-Tandem	
2012	Wu, Wenzhong	TUNL-HIGS	
2013	Mueller, Jonathan	TUNL-HIGS	Postdoc, NC State Univ., nuclear engineering
North Carolina State University			
2006	Xu, Yan-Ping	LANSCE(LANL)	Associate Research Scientist, Columbia University
2007	Poole, John	TUNL-Tandem	
2007	Sheets, Steven	DANCE(LANL)	Scientists, LLNL
2009	Chyzh, Andrii	DANCE(LANL)	Postdoc, LANL

Year	Name	Ph.D. Research Facility	Current Position (if known)
2009	Kephart, Jeremy		Postdoc, PNNL
2010	Baramsai, Bayarbadrakh	DANCE(LANL)	Financial Advisor, Goldman & Sachs
2010	O'Shaughnessy, Christopher	NIST	Postdoc, UNC
2012	Holley, Adam	LANSCE(LANL)	Postdoc, Indiana Univ.
2012	Pattie, Robert	LANSCE(LANL)	Postdoc, NCSU
2013	Schelhammer, Karl	LANSCE(LANL)	
2013	Walker, Carrie	DANCE(LANL)	Postdoc, LANL
2014	Gooden, Matthew	TUNL-Tandem	Postdoc, LANL
2014	Leviner, Lance		Private Industry
2014	Palmquist, Grant	PULSTAR-Reactor	Private Industry
TUNL University of North Carolina			
2007	Boswell, Melissa	TUNL-HIGS	Postdoc, LANL
2008	Angell, Christopher	TUNL-HIGS	Japan Atomic Energy Agency
2009	Bertone, Peter	TUNL-LENA	NASA, science research office
2009	Daniels, Timothy	TUNL-Tandem	Mechanical Eng., SLAC
2009	Newton, Joe	TUNL-LENA	Duke University Med. Center
2010	Longland, Richard	TUNL-LENA	Asst. Prof., NC State Univ.
2011	Arnold, Charles	TUNL-HIGS	Staff Scientist, Los Alamos National Laboratory
2011	Cesaratto, Johnny	TUNL-LENA	Postdoc, SLAC/CERN, Accelerator Research
2011	Couture, Alexander	TUNL-Tandem	Staff scientist, Savannah River Lab, Aiken, SC
2012	Hammond, Samantha	TUNL-HIGS	Postdoc, Penn. State Univ. (assigned to DTRA)
2012	McMulllin, Sean	TUNL-Tandem	Postdoc, Purdue Univ.
2012	Tompkins, Jeromy	TUNL-HIGS	Staff Scientist, FRIB
2013	Daigle, Stephen	TUNL-LENA	
2013	Finnerty, Padraic	TUNL-KURF	Staff Scientist at Applied Rsearch Associates, Inc (defense & space)
TUNL Students from other Universities, supervised by TUNL faculty			
2009	Zhang, Jianfeng	TUNL-HIGS	
2009	Leber, Micheller	TUNL-HIGS	Physics education, high school, southern calif.
2012	Schubert, Alexis		Postdoc
2013	Zimmerman, William	TUNL-HIGS	Postdoc, Duke
University of Kentucky			
2007	Choudry, Sadia Naeem	UK	Teacher, Jefferson County Public Schools, Louisville KY
2008	Mukhopadhyay, Sharmistha	UK	Assoc. Prof. and Head of Department at Institute of Mathematical Sciences, CIT, Chennai, India
2008	Elhami, Esmat	UK	Assistant Prof. at University of Winnipeg
2014	Crider, Benjamin Patrick Sledd	UK	Postdoctoral Researcher at NSCL, MSU
2014	Peters, Erin Elizabeth	UK	Postdoc/Part-time Instructor at University of Kentucky
University of Massachusetts Lowell			
2006	Roldan, Carlos	Gammasphere (ANL)	
2007	Ji, Chuncheng	Gammasphere (ANL)	
2009	Shirwadkar, Urmila	Gammasphere (ANL)	Scientist, Radiation Monitoring Devices, Inc., Watertown, MA
2010	Alimeti, Afrim	Gammasphere (ANL)	
2012	Hota, Sankha	Gammasphere (ANL)	Postdoc, Australian National University, Canberra
2014	D'Olympia, Nathan	U Mass	Scientist, Passport Systems, Inc., Billerica, MA
University of Notre Dame			
2006	Couture, Aaron	UND	Staff member
2006	Lee, Hye Young	Louvain (Belgium)/UND	Staff member Los Alamos National Laboratory
2007	Skorodumov, Boris B.	UND	Asst. Vice President Barclays Capital, New York
2007	Strandberg, Elizabeth	UND	Lockheed Martin Aeronautics Company
2007	Triambak, Smarajit	CENPA(UW)	SARChI Chair Professor, University of the Western Cape, South Africa
2007	Wang, Xiaofeng	Gammasphere (ANL)	Adjunct Lecturer at California Polytechnic in San Luis Obispo, CA
2008	Couture, Jennifer	UND	Homemaker
2008	Li, Tao		Quantitative Researcher Knight Capital
2009	Palumbo, Annalia	UND	Vist. Asst. Professor Central Michigan University
2010	LeBlanc, Paul	UND/LUNA (Gran Sasso)	CSE Icon
2010	O'Brien, Shawn Patrick	RCNP (Osaka)	Central Intelligence Agency, Washington, DC
2010	Quinn, Matthew A.	NSCL(MSU)	Radiation Safety, Fermi National Laboratory
2010	Robertson, Daniel J	UND	Research Professor, University of Notre Dame
2010	Schmitt, Christopher J.	UND	Asst. Professor, Oak Ridge Community College
2011	Almaraz Calderon, Sergio Jesus	UND	Asst. Professor, Florida State University
2011	Best, Andreas Christian	UND	Research Associate, INFN Gran Sasso, Italy
2011	deBoer, Richard James, II	UND	Research Associate, University of Notre Dame
2012	Kontos, Antonio	UND	Research Associate, MIT
2013	Bowers, Mathew	UND	Industry, Bechtel National, Inc
2013	Uberseder, Ethan	UND	Research Associate, Texas A&M University
2013	Ayangeakaa, Akaa Daniel	Gammasphere(ANL)	Research Associate, Argonne National Laboratory
2014	Bucher, Brian T.	UND	Research Associate, Lawrence Livermor National Laboratory
2014	Smith, Karl	UND	Research Associate, University of Tennessee
2015	Li, Quan	UND	Actuarial Analyst, Windhaven Insurance

Year	Name	Ph.D. Research Facility	Current Position (if known)
2015	Patel, Darshana	RCNP(Osaka)	Medical Physicist, MS Anderson Cancer Center
University of Washington			
2006	Bacrania, Minesh	CENPA(UW)	Private Bussiness, self employed in Santa Fe, NM
2008	Sjue, Sky	CENPA(UW)	LANL staff (scientist 2)
2008	Mohrmann, Erik	CENPA(UW)	Department Chair, DigiPen Institute of Technology, Seattle WA
2010	Sallaska, Anne L.	CENPA(UW)	NIST staff at Gaithersburg, MD

Table 1: ARUNA Ph.D. Graduates 2006–1/2015 in experimental low-energy nuclear physics, nuclear astrophysics, fundamental symmetries (as far as connected to accelerator-based research) and applications. Their current position and institution is listed where known.

7 The ARUNA facilities

ARUNA facilities provide a unique set of nuclear probes that are often not available at national facilities. They offer flexibility and quick response to new research developments and challenges.

The connection of research goals at the ARUNA facilities to the goals of the national community allows for a synergy of scales, where new detector and methodological developments can be pursued at ARUNA facilities, which in turn lead to new opportunities at the national user facilities. ARUNA facilities have a history of developing new techniques, from the first in-flight radioactive beam facility, Twinsol at Notre Dame, to the currently highest sensitivity cross section measurements for astrophysics at LENA (TUNL). In many other examples, ARUNA labs have been used to push the boundaries of scientific inquiry and have great opportunities to continue to do so in the future.

Major upgrades are ongoing or proposed at ARUNA laboratories;

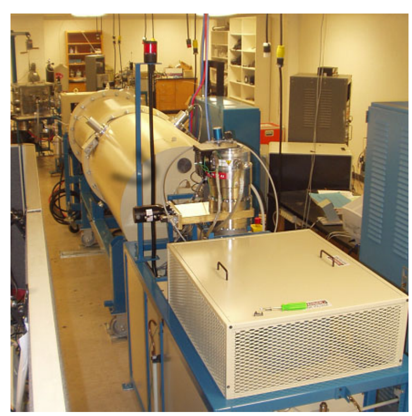
- The stopped and re-accelerated radioative beam facility (T-Rex) at Texas A&M university, with sufficient energy and beam quality for multi-fragmentation reaction studies is approaching completion.
- A high-intensity heavy-ion accelerator and recoil separator, St. ANA / St. George, are nearing production phase at the Notre Dame facility.
- A high-resolution high-acceptance magnetic spectrograph is being installed at Florida State University.
- HIγS at TUNL is pursuing a staged intensity and quality upgrade for the monoenergetic γ–ray beam.
- The CASPAR underground accelerator at the Sanford Underground Research Facility in South Dakota that is being developed by Notre Dame and will be operated by a collaboration of ARUNA groups.

Florida State University, John D. Fox Accelerator Laboratory

- 9-MV FN tandem accelerator, Pelletron charged
- 9-MV Superconducting Linear Accelerator as booster, using 14 split-ring niobium on copper cavities
- Ion beam mass range and maximum energy: A$\leq$7: 10 MeV/u, A$\leq$16: 8 MeV/u, A$\leq$40: 5 MeV/u
- In-flight radioactive beam facility RESOLUT; exotic beams between mass 6 and 30
- Germanium detector array, 3 Clover + 10 conventional, anti-Compton detectors
- New project: split-pole spectrograph
- Planned linac upgrade to 14 MV, extending RIB reach to mass 50

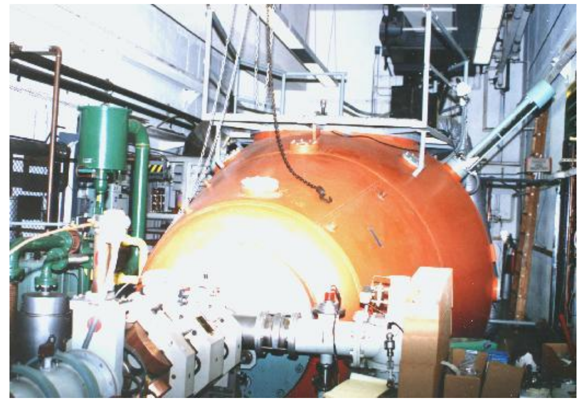
Hope College, Ion Beam Analysis Laboratory

- 1.7-MV tandem accelerator for ion beam analysis
- Programs in materials analysis



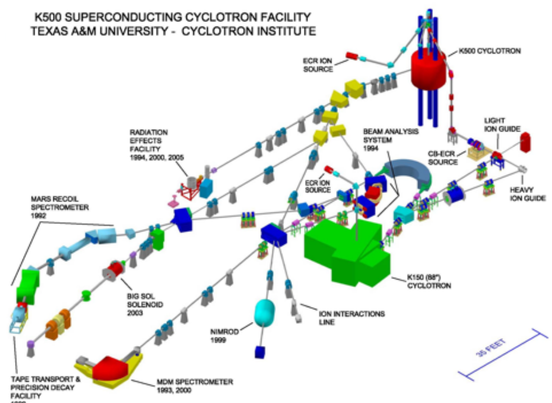
Ohio University, John E. Edwards Laboratory

- 4.5-MV T-type tandem accelerator, Pelletron charged
- Beams of p,d, ^{3}He, ^{4}He, heavy ion beams
- 2 target rooms
- 30-m long, time-of-flight tunnel
- Particularly well equipped for time-of-flight experiments and neutron detection



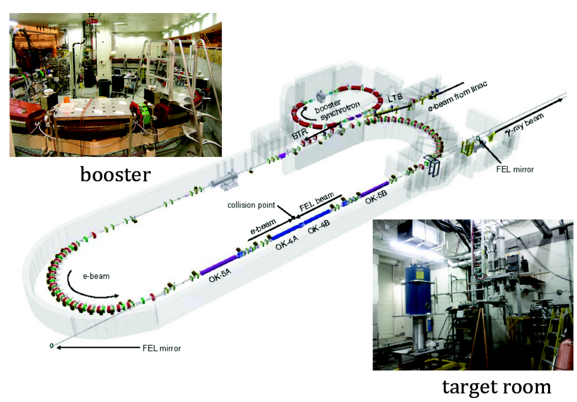
Texas A&M Cyclotron

- K-150 cyclotron
- K-500 superconducting cyclotron
- ECR ion sources
- Negative ion source
- Mars recoil spectrometer, production and separation of radioactive beams
- Nimrod high-efficiency multi-particle detector
- Precision on-line β-decay γ-detector system
- MDM spectrometer
- FAUST-QTS
- Radiation effects facility
- STARLiTeR array
- Upgrade-project, ongoing: T-REX, Gas-stopping and re- accelerated RIB facility
- New project: TAMU-trap, studying delayed proton decays
- New project: Sassyer / Aggie gas-filled spectrometer for super heavy element studies

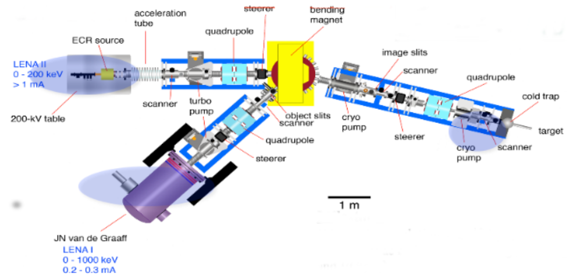


TUNL-HIγS

- World's most intense accelerator-driven γ–ray source
- 1.2-GeV e-storage ring free electron laser (FEL)
- γ-ray beam through Compton-backscattering of FEL photons
- Linear and circular polarized mono-energetic γ-ray beams
- Program for γ-induced astrophysical reaction rates
- Program in nuclear structure (high-resolution nuclear resonance fluorescence, photofission and Compton scattering)
- Upgrade-project: Increase capacity of FEL-wigglers, increase photon energy to 120 MeV
- Upgrade-project: HIγS2, x100 increase in γ-ray beam intensity with optical cavity pumped with external laser

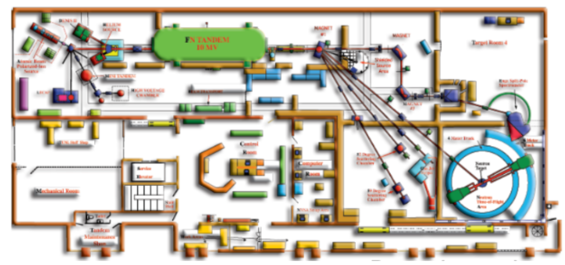


TUNL-LENA, Laboratory for Experimental Nuclear Astrophysics



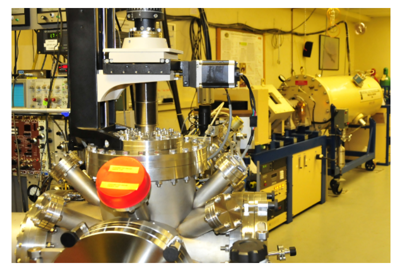
- 2 High-intensity low-energy accelerator systems
- LENA I, JN van de Graaff accelerator, 1 MeV, 0.3 mA beam current
- LENA II, 200-kV platform, ≤ 1 mA beam current
- High-resolution Ge–detector, inside NaI calorimeter
- Program to measure (p, γ) reactions for stellar evolution and Nova- and X-ray burst nuclear reaction rates
- Upgrade-project: RF-Pulsing ECR source, improved accelerator tube
- Upgrade-project: replacement of JN accelerator

TUNL-Tandem Laboratory



- 10-MV FN tandem accelerator, Pelletron-charged
- p,d, ^{3}He, ^{4}He beams
- Secondary neutron beams
- Upgrade-project: re-commissioning of split-pole spectrograph

Union College, Ion Beam Analysis Laboratory



- 1.1-MV tandem accelerator for ion beam analysis

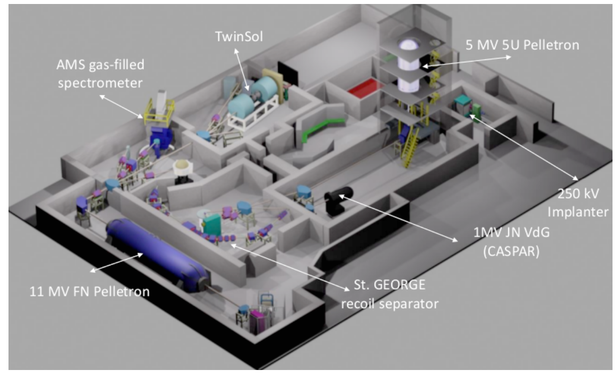
University of Kentucky, Accelerator Laboratory

- 7-MV single-ended Van de Graaff accelerator
- p,d,^{3}He, ^{4}He beams
- Terminal and post-acceleration bunching system, sub-ns resolution
- In-flight production of mono-energetic neutrons
- Shielded setup for high-resolution γ–ray spectroscopy after inelastic neutron scattering; neutron time-of-flight capabilities

University of Massachusetts-Lowell, Radiation Laboratory

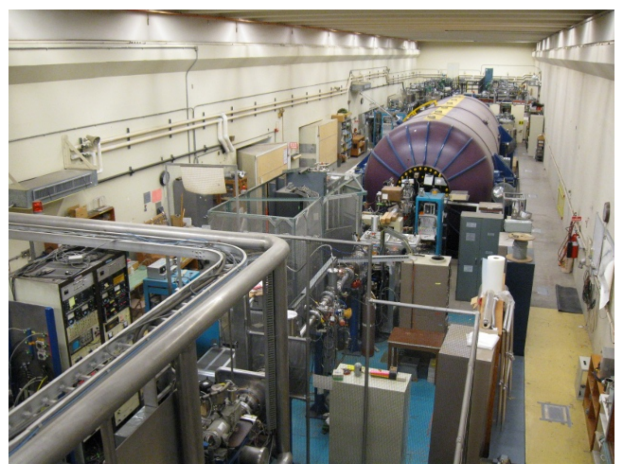
- 5.5-MV single-ended Van de Graaff accelerator
- 100μA DC beam
- Terminal bunching system, sub-ns resolution
- In-flight production of mono-energetic, pulsed neutron-beam
- Programs in neutron detector development
- 1-MW research reactor, hot-cell with remote manipulators
- 100-kCi ^{60}Co source for γ irradiation
- Programs in neutron and segmented-Ge detector development

University of Notre Dame, ISNAP, Institute for Structure and Nuclear Astrophysics



- 11-MV FN tandem accelerator, Pelletron charged
- TwinSol in-flight radioactive beam facilty
- Accelerator mass spectrometry with ion source and gas-filled spectrometer
- 250 kV accelerator for implantation and low energy studies.
- Recent project: 5-MV single-ended Pelletron with ECR source (St. Ana) is operating
- Recent project: St. George recoil seperator for Astrophysical reaction rate measurements
- New project: Move 1-MV CASPAR accelerator deep underground, to Sanford Underground Research Facility
- Planned project: Isotope production with 24-MeV medical cyclotron for ion-trap mass measurements

University of Washington, CENPA, Center for Experimental Nuclear Physics and Astrophysics



- 10-MV FN tandem acclerator, Pelletron-charged
- World-record production of ^{6}He isotope, used for β–decay measurement in Laser-trap

8 Summary

ARUNA laboratories have active and innovative programs in low-energy nuclear science and nuclear astrophysics, with a focus on the big questions of the field. The ARUNA laboratories of today have re-invented their experimental programs many times over and, in doing so, have often defined the forefront of methodical developments, such as in-flight radioactive beam facilities. ARUNA laboratories have leadership programs in the areas of nuclear astrophysics and fundamental symmetries. The programs in nuclear structure and nuclear reactions are complementary to, or synergistic with, the efforts at the two national user facilities of low-energy nuclear science and nuclear astrophysics. The scientists of ARUNA operate the accelerator facilities because of the multiple scientific opportunities and the scientific flexibility they offer for innovative research and development.

The ARUNA laboratories provide an ideal environment to develop new experimental techniques for research with exotic beams. Present examples for such development projects include the ANASEN active-target detector developed at FSU, and techniques for a direct measurement of astrophysical reaction rates at St. Ana / St. George, which can be applied directly to the measurements with the to-be-developed SECAR separator for FRIB. Another example is the development of high intensity low energy beams, which can be utilized for the underground accelerator project.

During the period of 2006-2012, 40% of the doctoral degrees in low-energy nuclear science and nuclear astrophysics were granted at the groups of the ARUNA laboratories (including the Yale University group)[1]. With their flexible scheduling and fast turn-around, ARUNA laboratories are ideal places to provide graduate education on the full depth of experimental science, encompassing development projects at the accelerator, experiments, data analysis and scientific interpretation.

Early exposure of undergraduate students to fundamental and applied nuclear methods is a big factor in addressing the workforce needs in nuclear science and nuclear applications. The presence of ARUNA laboratories on university campuses make them ideal places for undergraduate research projects. All ARUNA labs support undergraduate research and most are hosts to external groups from undergraduate colleges. The broad range of applied programs creates collaborations with non-nuclear and non-science faculty and students, leading to a broader appreciation for the benefits of nuclear science. ARUNA labs are natural places to rejuvenate the nuclear workforce and represent nuclear science in society.

References

[1] NSAC Subcommittee Report on the Implementation of the 2007 Long-Range Plan, January 18, 2013
http://science.energy.gov/~/media/np/nsac/pdf/20130201/
2013_NSAC_Implementing_the_2007_Long_Range_Plan.pdf

[2] NSAC Workforce Subcommittee Report, July 18, 2014 J. Cizcewski (chair)
http://science.energy.gov/~/media/np/nsac/pdf/docs/2014/NSAC_workforce_jul-18-2014.pdf